Mitglied der Helmholtz-Gemeinschaft

Ultimate precision X-ray spectroscopy of hadronic atoms

Detlev Gotta

Institut für Kernphysik, Forschungszentrum Jülich / Universität zu Köln

GGSWBS'14, Tbilisi, Georgia

6th Georgian – German School and Workshop in Basic Science - lecture

July 10, 2014

- **MOTIVATION**
- **EXOTIC ATOM**
- **EXPERIMENTAL APPROACH**
- **SOME RESULTS**

- **MOTIVATION**
- **EXOTIC ATOM**
- **EXPERIMENTAL APPROACH**
- **SOME RESULTS**

PIONS, NUCLEONS, ... , CHIRAL PERTURBATION THEORY, ...

J. Gasser et al. / Nucleons with chiral loops

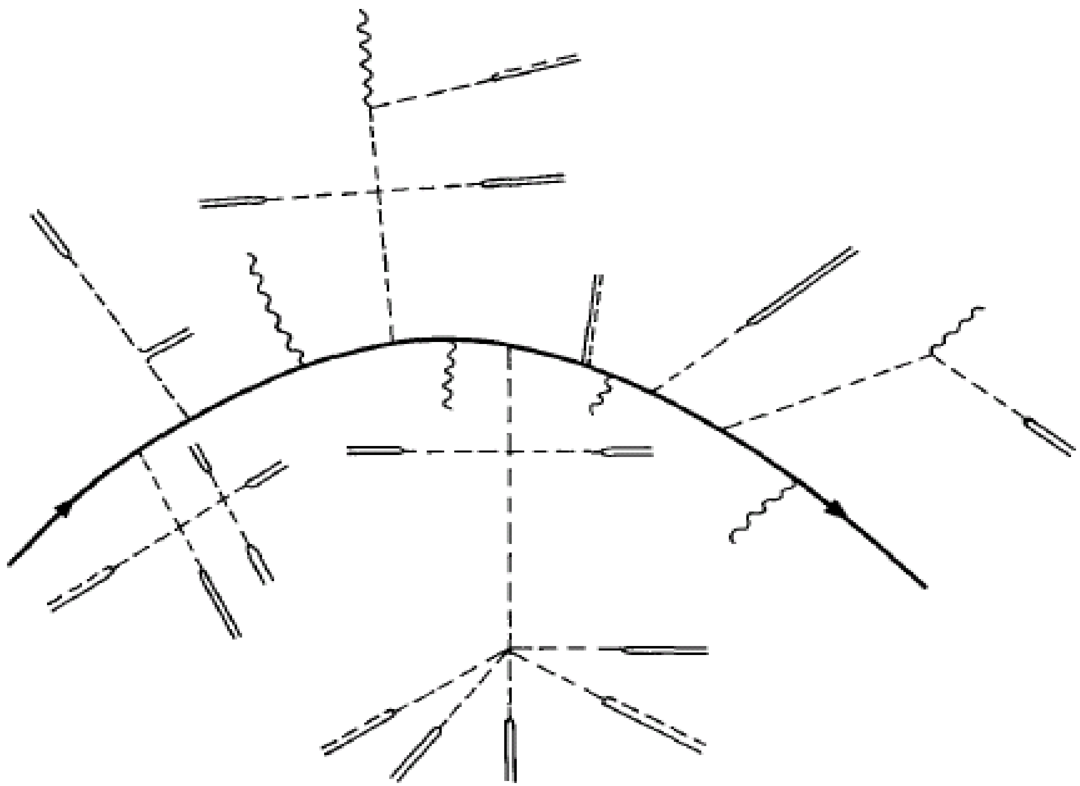
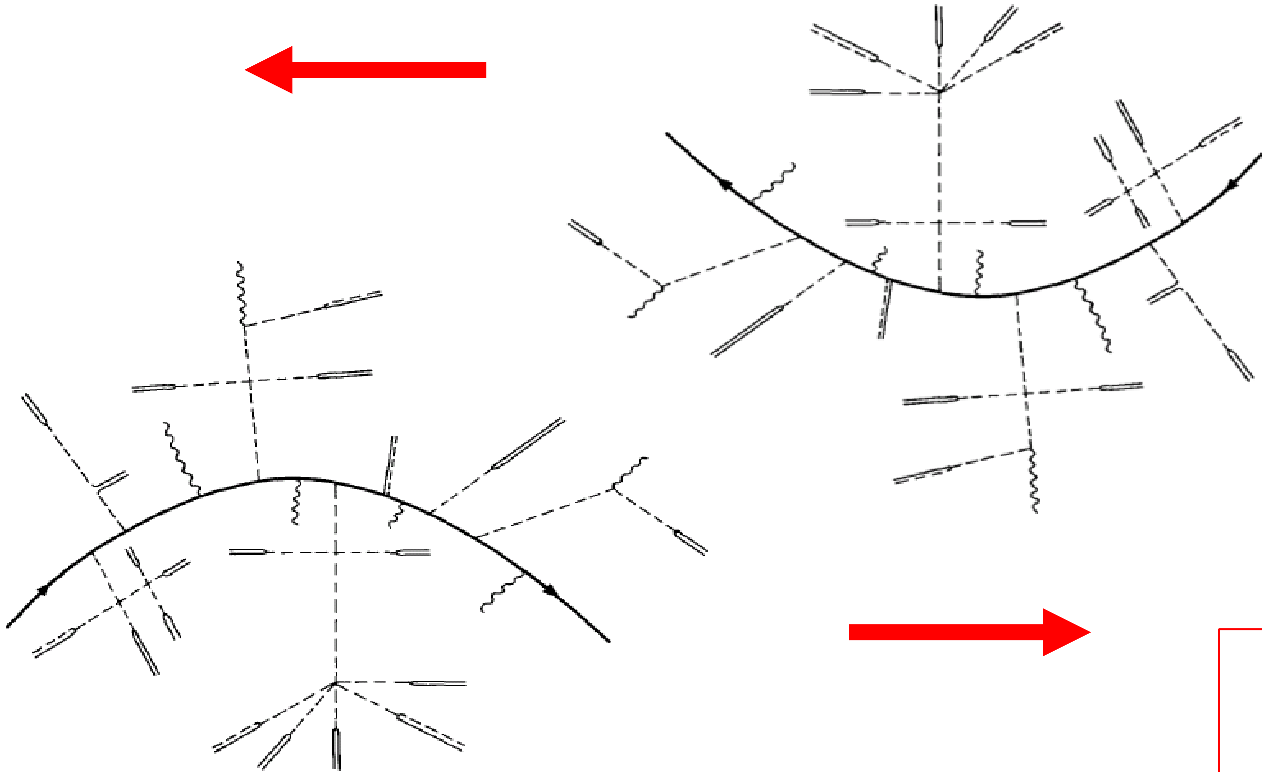


Fig. 1. A typical term in the expansion (3.7) of the nucleon propagator. ——►—— nucleon; - - - pions; ~~~ vector current; =-=- axial vector current; --⊏ pseudoscalar density; ═══ scalar density.

PIONS, NUCLEONS - INTERACTION in terms of QCD



$N \Leftrightarrow N$

$\pi N \Leftrightarrow \pi N$

ANTINUCLEON - NUCLEON, … , no microscopic theory

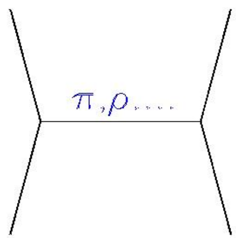
$$V_{\text{Coulomb}} + U_{\text{hadronic}}$$

U_{hadronic} = meson exchange + annihilation

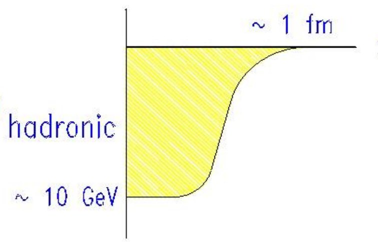
scattering: $\bar{p}p \leftrightarrow \bar{p}p$, $\bar{p}p \leftrightarrow \bar{n}n$ | $\bar{p}p \rightarrow$ mesons

$NN \xrightarrow{\text{G-parity}} \bar{N}N$ | $U \propto a\,\rho(r)$

Re U_{hadronic}



Im U_{hadronic}



$\varepsilon,\Gamma \longleftrightarrow$ medium + long-range part of $\bar{N}N$ interaction

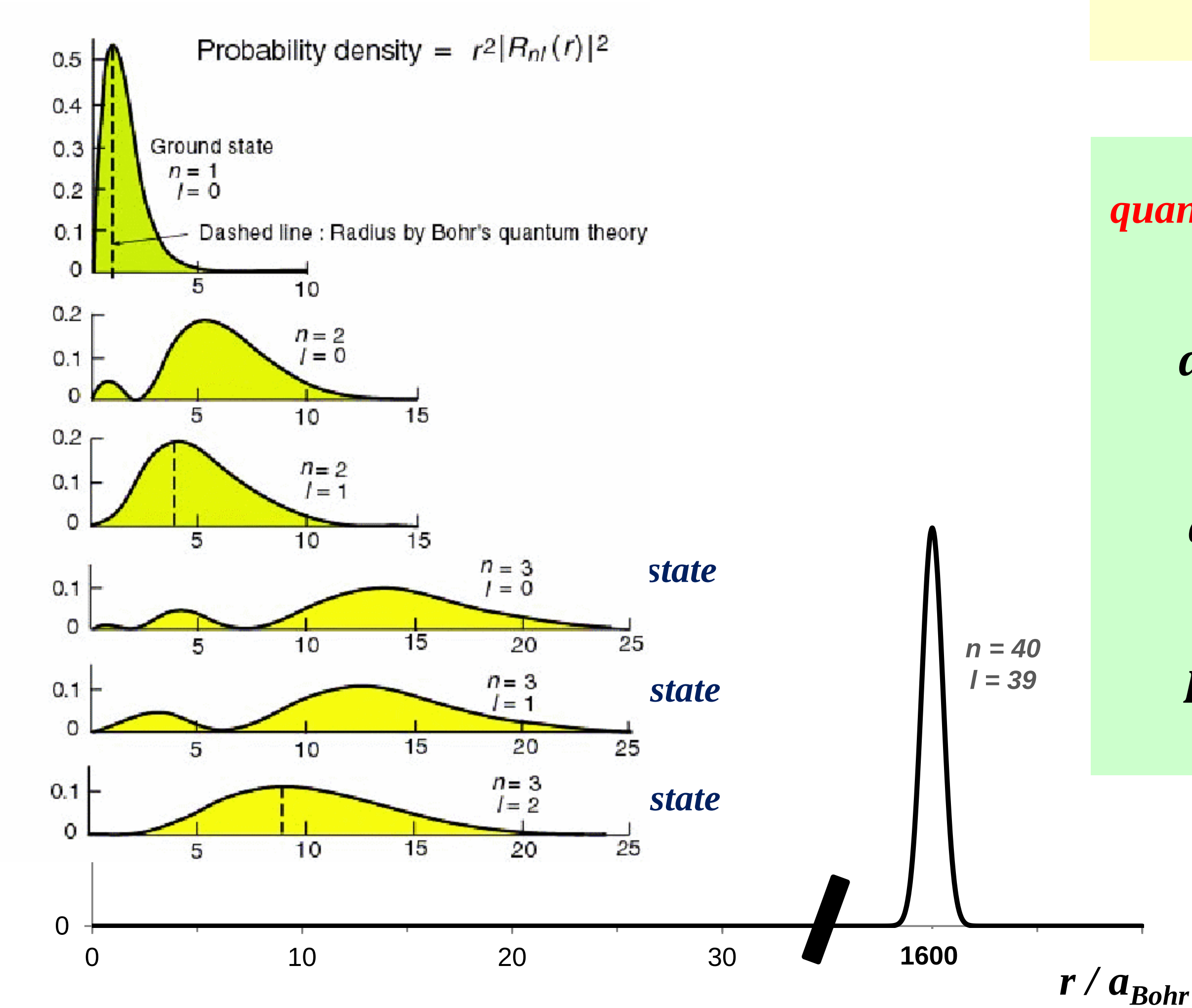
Buck, Dover, Richard, Ann. Phys. (NY) 121 (1979) 47

spin-spin "deuteron" ***no microscopic theory***
spin-orbit effects

☞ ***check spin dependence !***

- MOTIVATION
- **EXOTIC ATOM**
- EXPERIMENTAL APPROACH
- SOME RESULTS

ATOM



$$V_{Coulomb} = -\frac{Ze^2}{r}$$

quantisation of action: $E \cdot t = 2\pi\hbar$

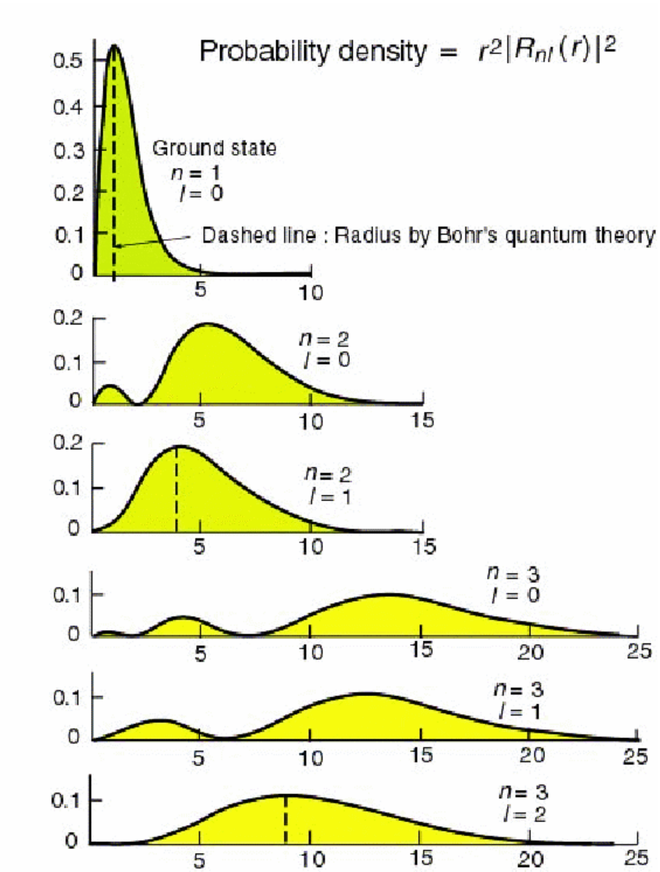
$$a_n = \frac{\hbar c}{m_{red}\, c^2 \alpha} \cdot \frac{n^2}{Z^2}$$

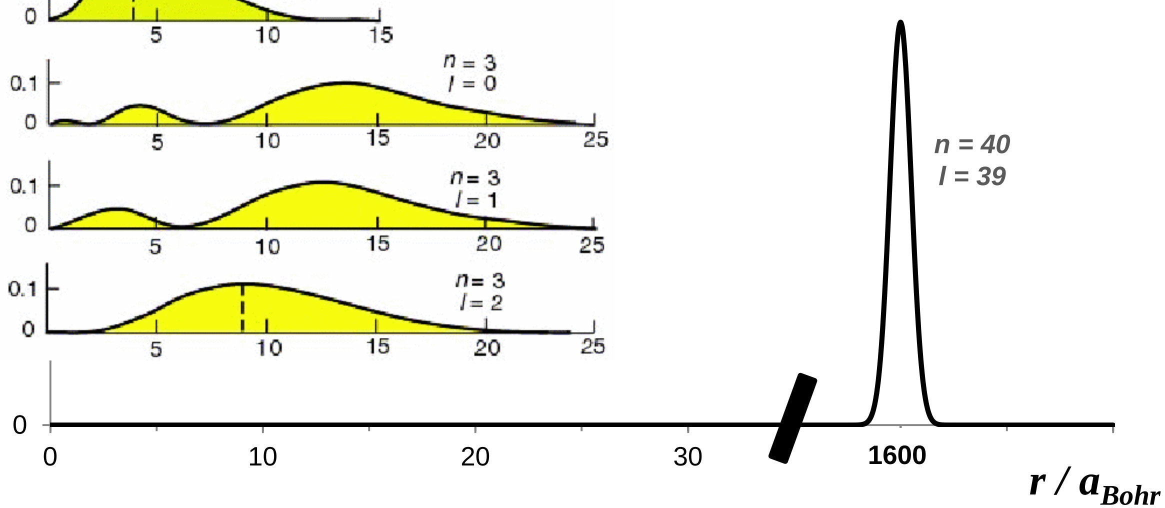
$$a_{Bohr} = \frac{\hbar c}{m_{red}\, c^2 \alpha}$$

$$B_n = -\, m_{red}\, c^2 \alpha^2 \cdot \frac{Z^2}{2n^2}$$

EXOTIC ATOM

replace electrons by heavier negatively charged particles



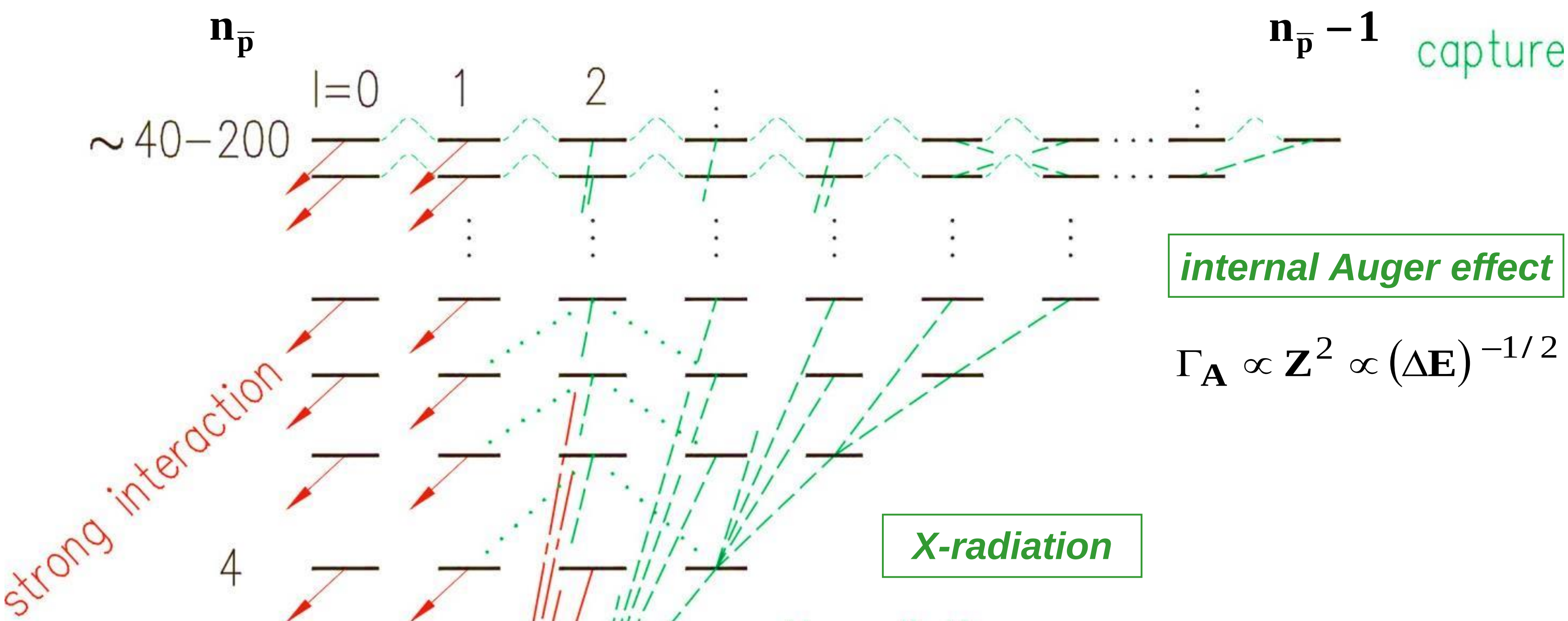


		m / MeV/c^2	B_1 / keV	"Bohr" radius a_0 / fm
atomic	e^-p	0.511	0.0136	$0.5 \cdot 10^5$
	μ^-p	105	2.6	279
	π^-p	140	3.2	216
	$\bar{p}\ p$	938	12.5	58
"nuclear" dimensions	$< r_p >$			0.8

$$a_{16}(\pi^-) \approx a_1(e^-)$$

$$a_{40}(\bar{p}) \approx a_1(e^-)$$

CAPTURE and DE - EXCITATION



$$\Gamma_A \propto Z^2 \propto (\Delta E)^{-1/2}$$

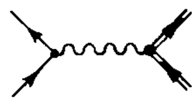
$$\Gamma_X \propto Z^4 \propto (\Delta E)^3$$

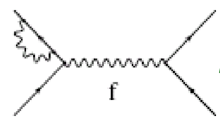
different de-excitation cascades for

leptons	**µ**	***pure electromagnetic cascade***
hadrons	**π, K, p, …**	***… + nuclear reactions for low l - states***

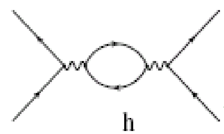
including STRONG INTERACTION

$$V_{Coulomb} = -\frac{Ze^2}{r} + \Delta EQED + V_{strong\ interaction}$$





self energy



vakuum polarisation

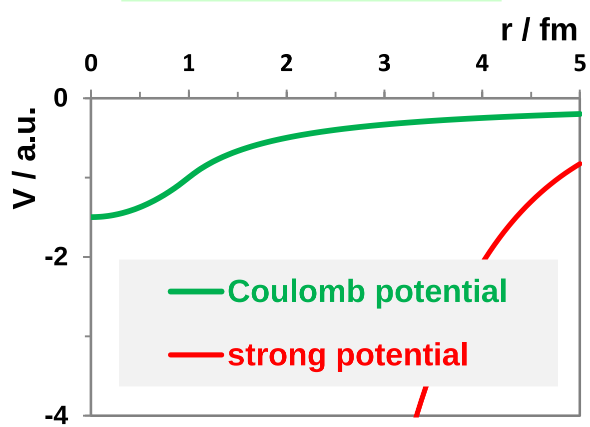
$m_\gamma = 0$

+ higher orders

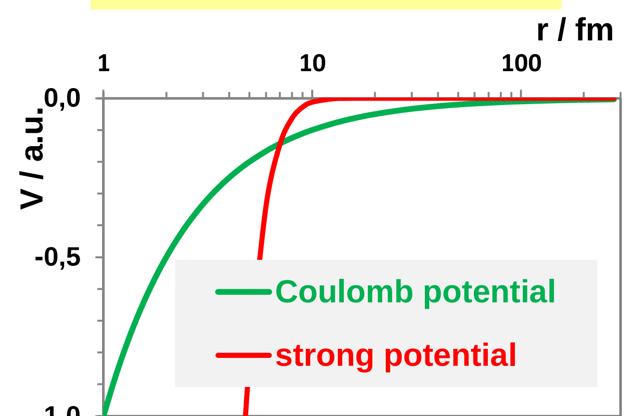
Yukawa potential

$$V_{strong} = g^2 \cdot \frac{e^{-\mu r}}{r}$$

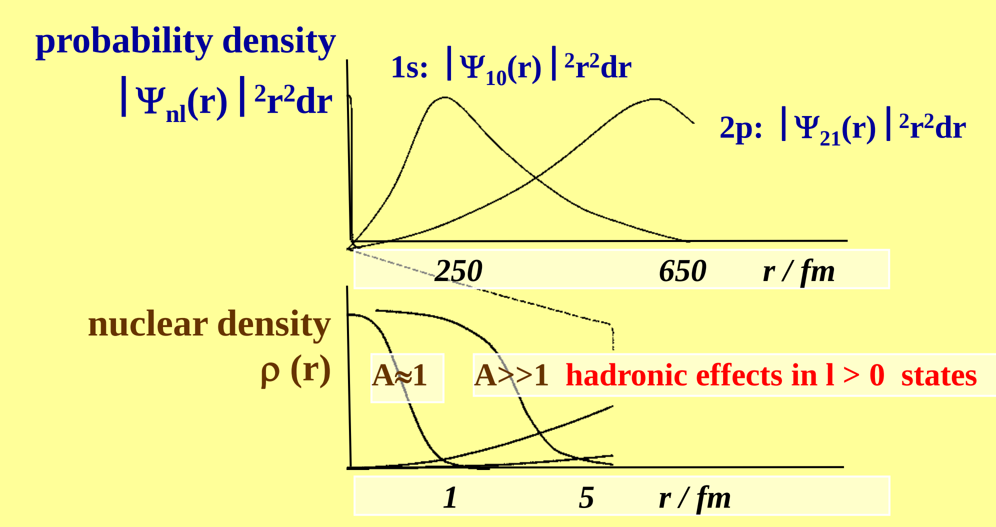
long range: $m_\gamma = 0$

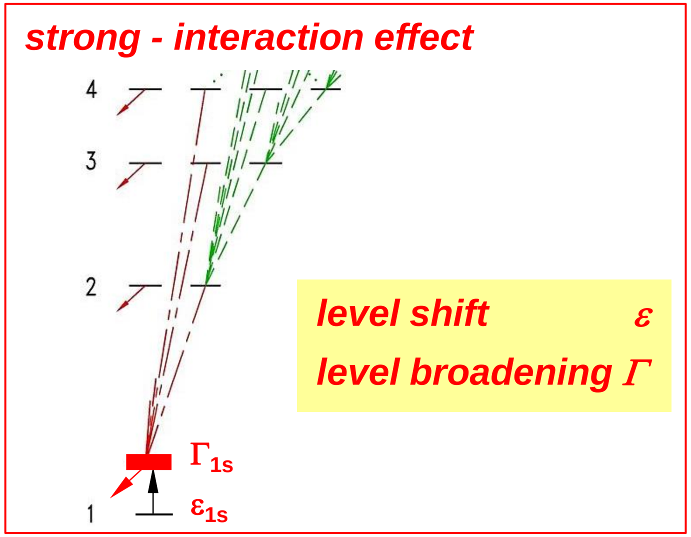


short range : $\mu = \frac{m_\pi c^2}{\hbar c}$



HADRONIC ATOM





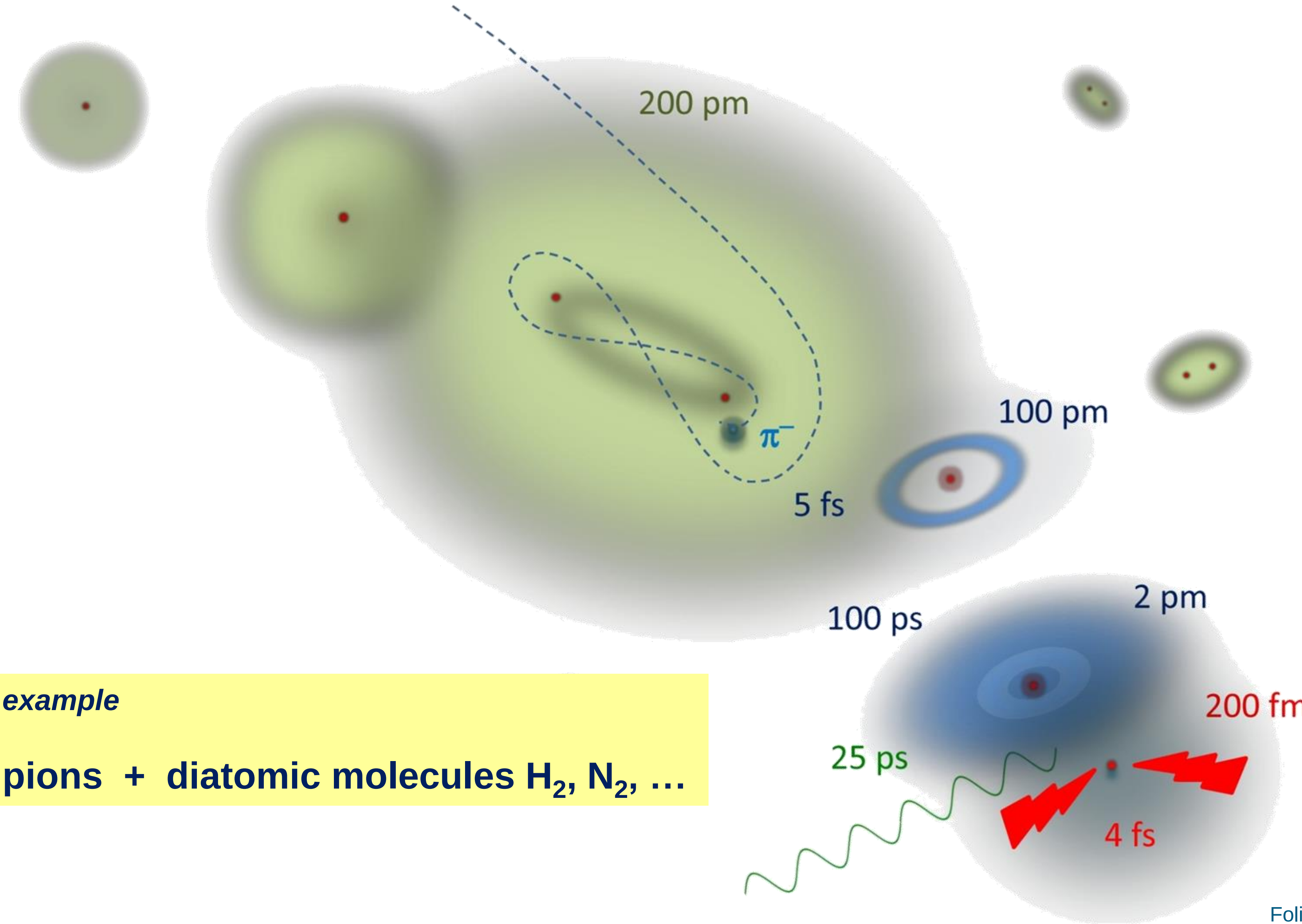
$$\Delta E_{strong} = \epsilon - i\frac{\Gamma}{2} = \int |\Psi_{nl}|^2 \, |V_{strong}| \mathrm{d}V \propto a_l \in \mathbb{C}$$

ΔE_{strong} *reduces to* *complex numbers*

- scattering length a_S for s-waves

- scattering volume a_p for p-waves

FATE OF HADRONIC ATOMS



example

pions + diatomic molecules H_2, N_2, …

- MOTIVATION
- EXOTIC ATOM
- **EXPERIMENTAL APPROACH**
- SOME RESULTS

APPROPRIATE TOOLS

TWO IMPORTANT EXAMPLES

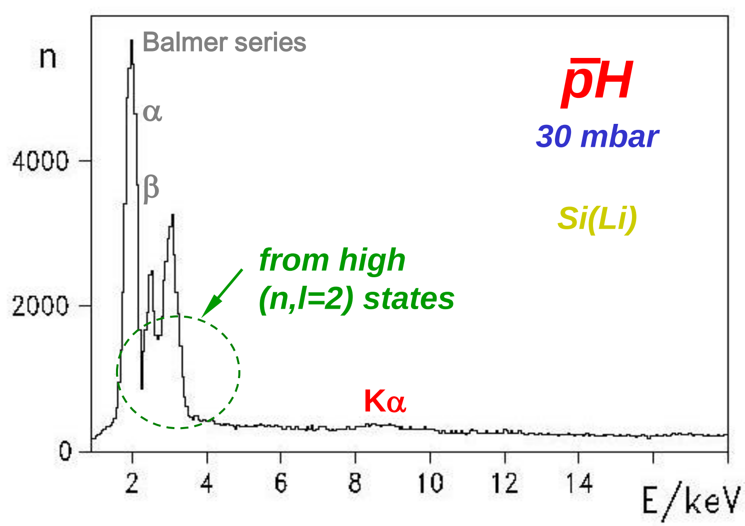
- ***pionic hydrogen***
- ***antiprotonic hydrogen***

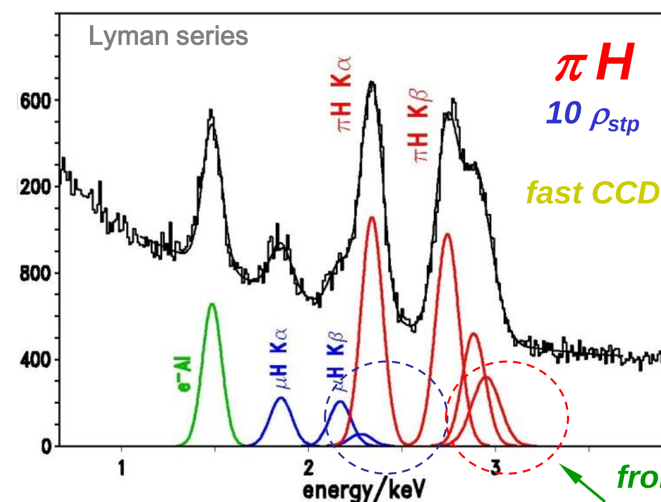
ENERGY RANGE access to strong interaction effects

crystal spectrometer

direct measurement

crystal spectrometer





from high
(n,l=1) states

$\varepsilon, \Gamma \approx$ 40 meV

$\approx$ 1 keV

$\approx$ 1 eV

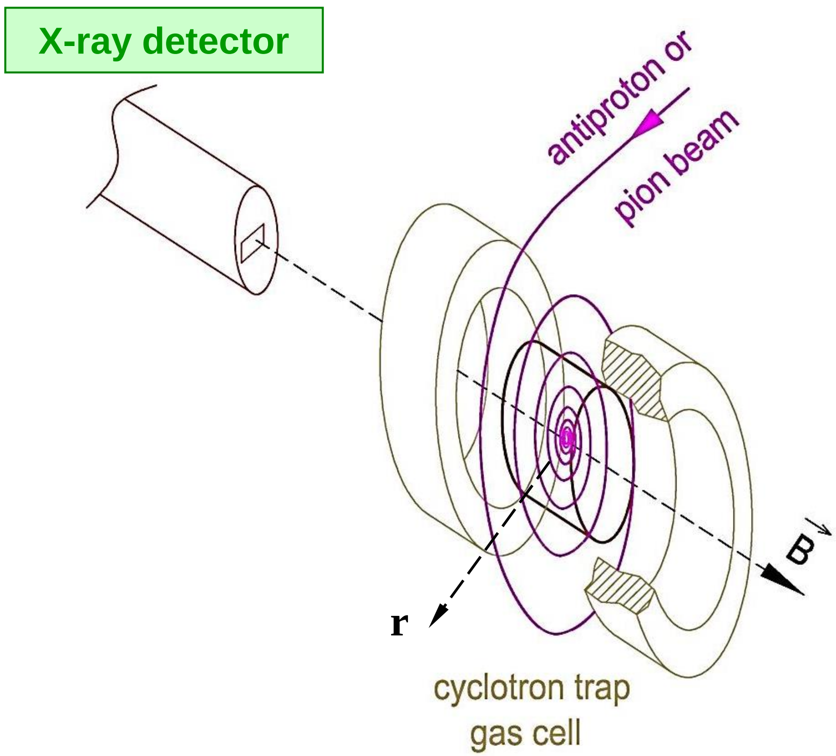
EXPERIMENT I

How to produce a suitable X-ray source

=

many of exotic atoms?

CYCLOTRON TRAP
concentrates particles



L. Simons, Physica Scripta 90 (1988), Hyperfine Int. 81 (1993) 253

"wind up" range curve

in a (weakly) focusing magnetic field

$$n = -\frac{\frac{\partial B}{B}}{\frac{\partial r}{r}} < 1 \qquad \textit{field index}$$

increase in <u>stop density</u>

compared to a linear stop arrangement

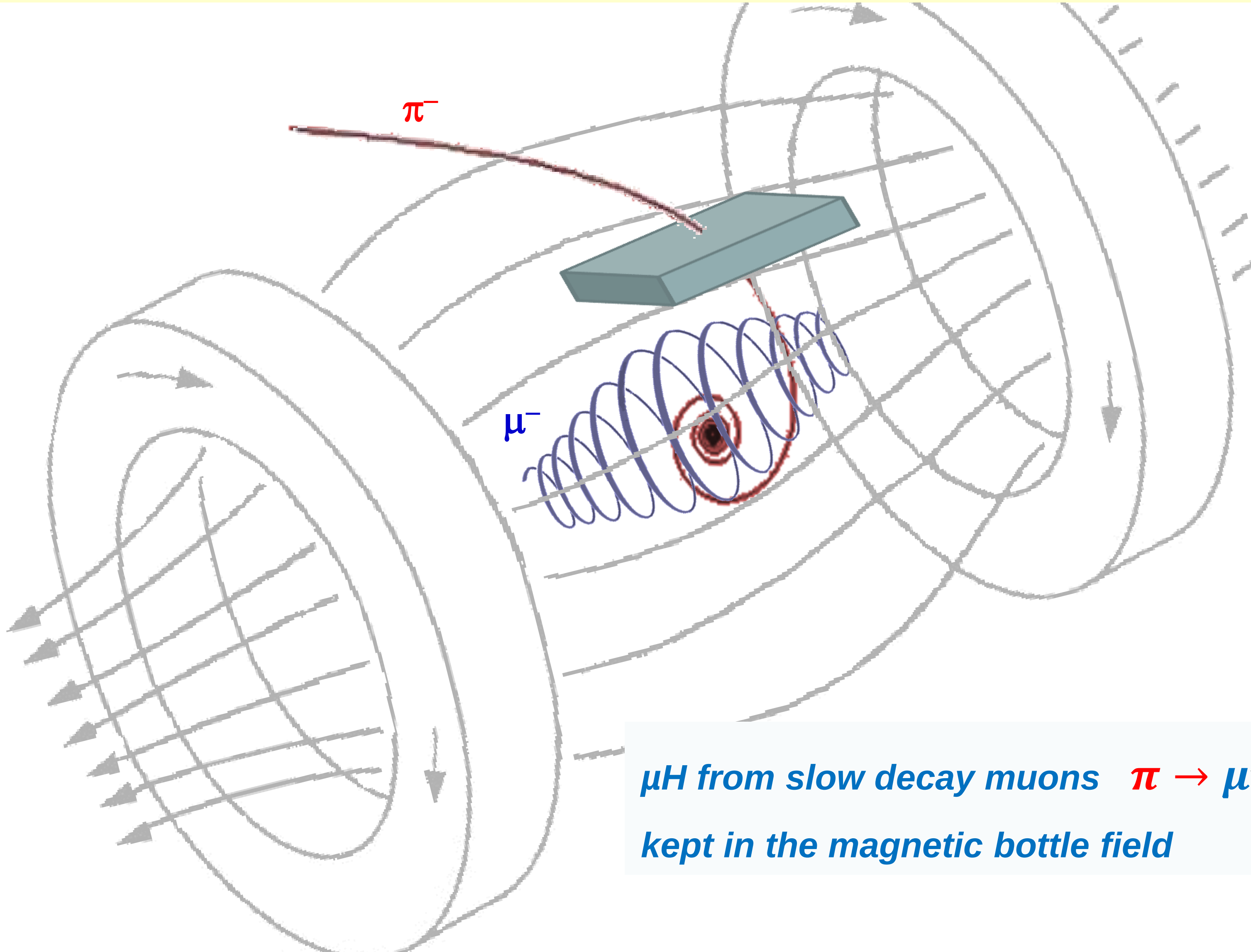
pions (PSI)	x 200
antiprotons (LEAR)	x 10^6

⇒ **high X - ray line yields**

⇒ **bright X - ray source**

CYCLOTRON TRAP

superconducting split-coil magnet

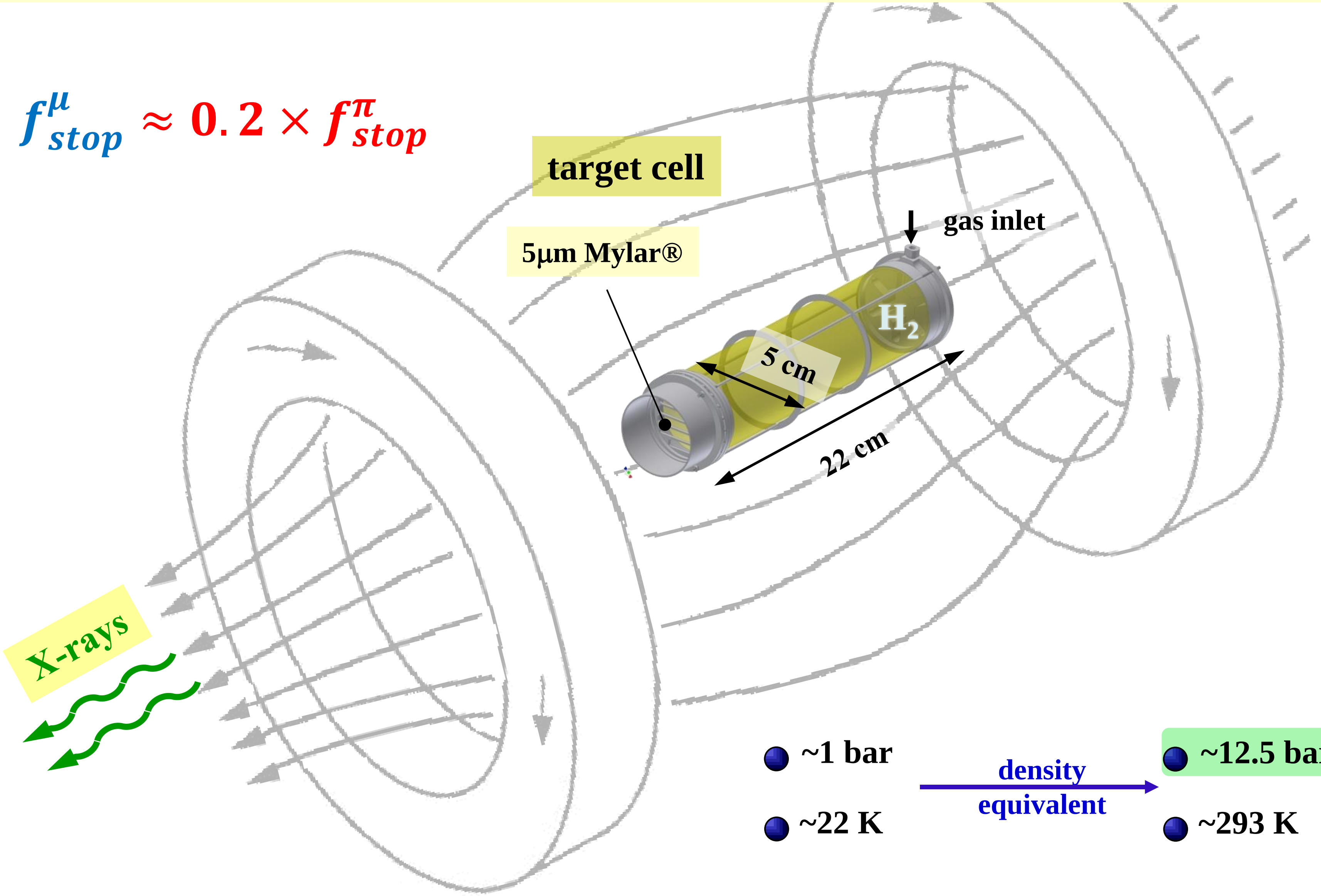


µH from slow decay muons $\pi \rightarrow \mu\nu$

kept in the magnetic bottle field

CYCLOTRON TRAP pion and muon setup

$$f^{\mu}_{stop} \approx 0.2 \times f^{\pi}_{stop}$$



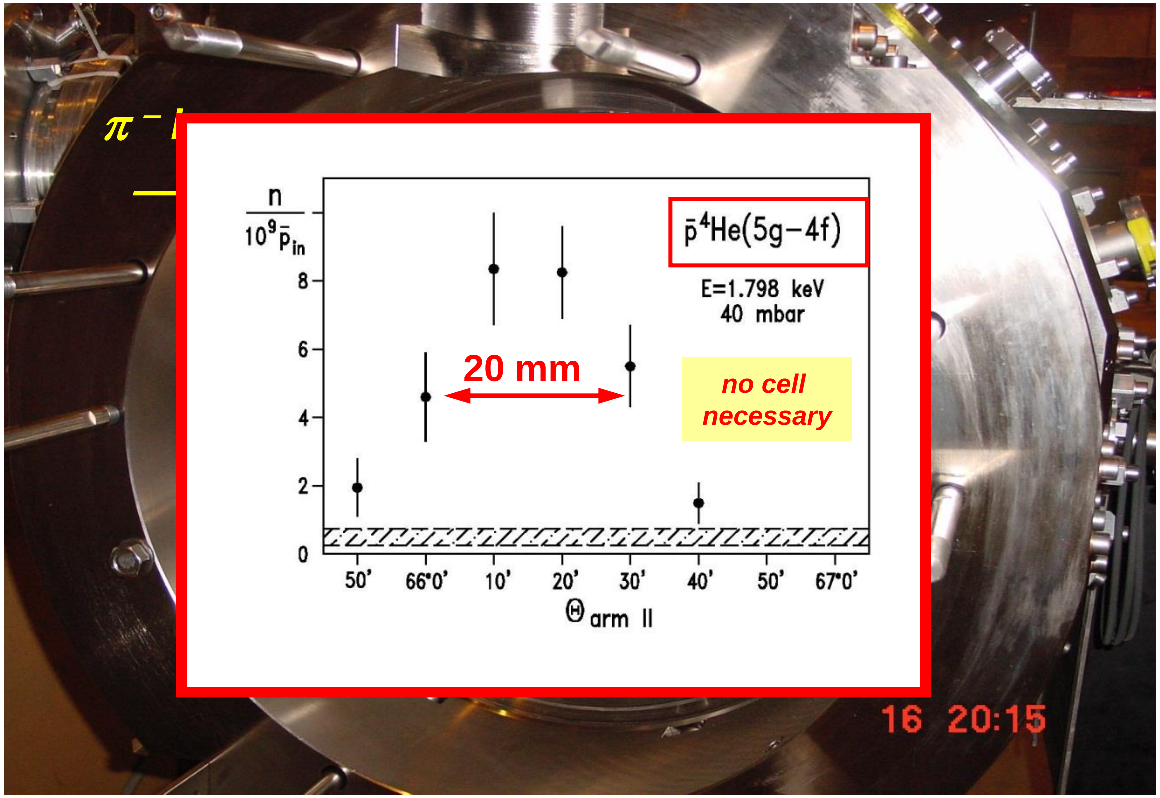
- ~1 bar
- ~22 K

density equivalent

- ~12.5 bar
- ~293 K

DEGRADERS and CRYOGENIC TARGET
inside
CYCLOTRON TRAP II

one half of yoke of super-conducting split coil magnet

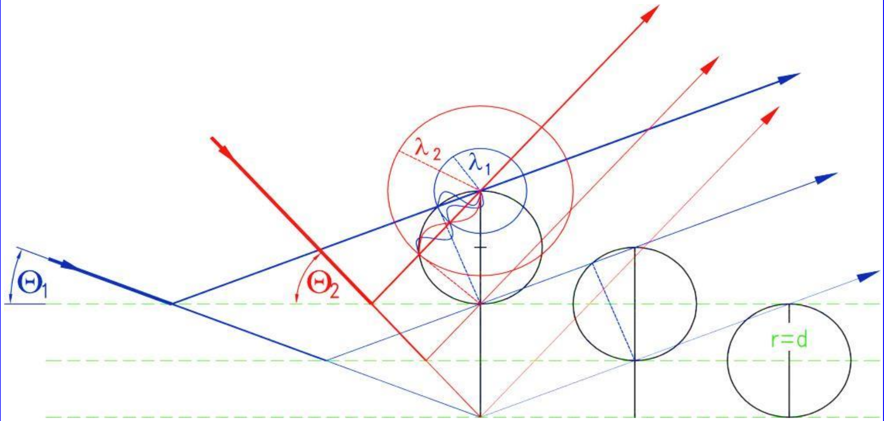


EXPERIMENT II

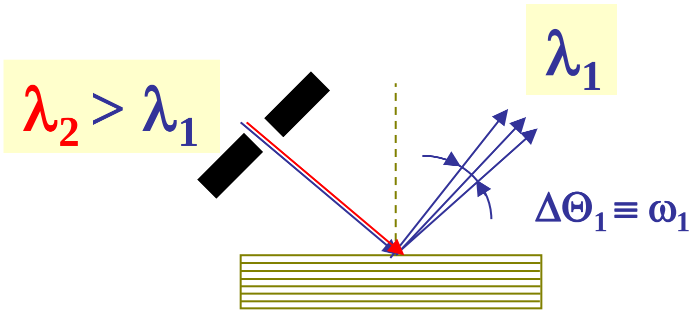
How to measure the resolution of the crystal spectrometer ?

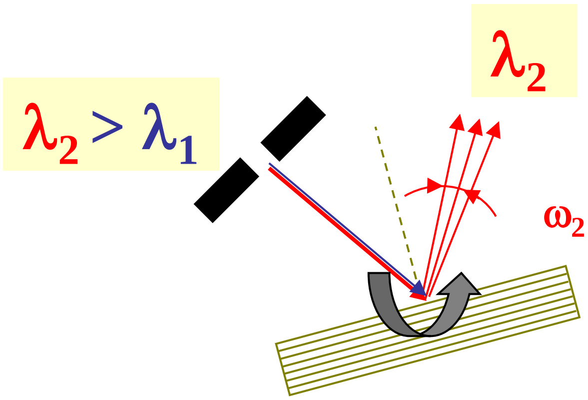
BRAGG'S LAW $n\lambda = 2d\cdot\sin\theta_B$

n	order of diffraction
λ	wave length
d	spacing of diffracting planes
θ_B	Bragg angle



ω angular spread of reflection



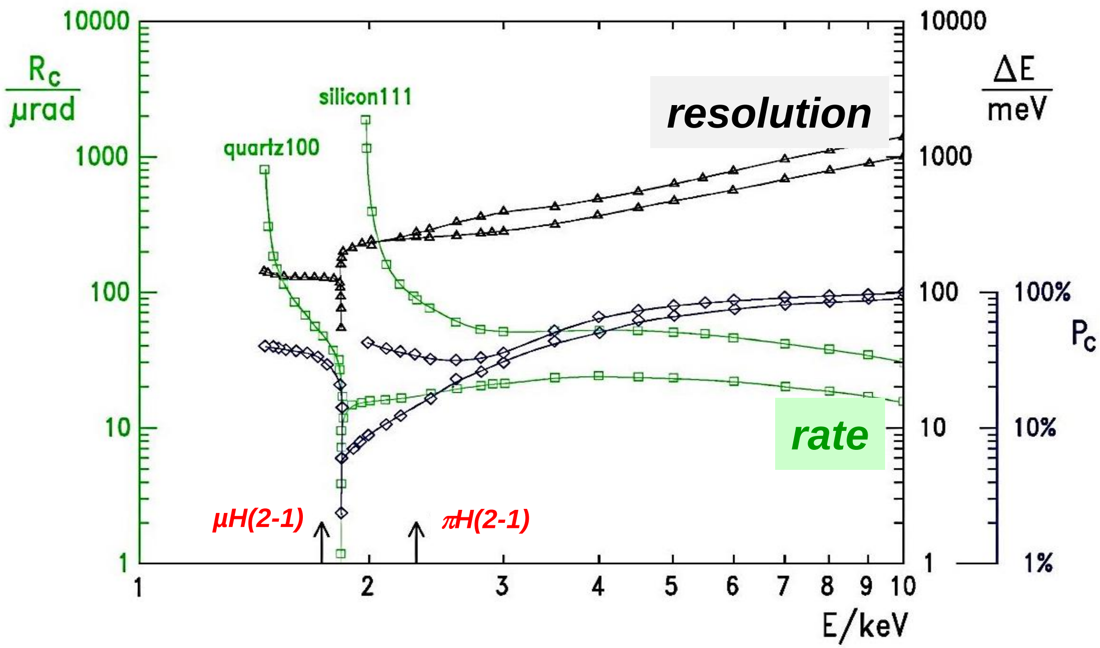


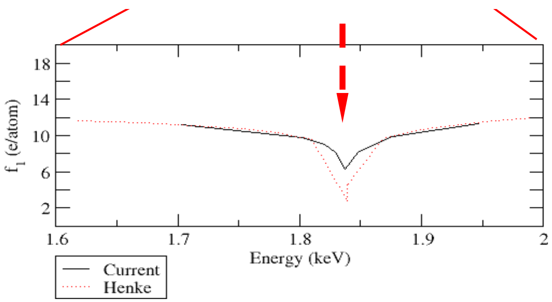
τ_e extinction length *coherent reflection*

τ_a absorption length *incoherent*

usually $\tau_e \ll \tau_a$

reflectivity R_C & energy resolution ΔE





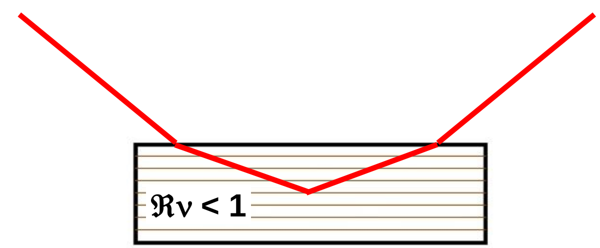
calculated by means
of diffraction theory

critical behavior close to absorption edges
(anomalous dispersion)

complex index of refraction

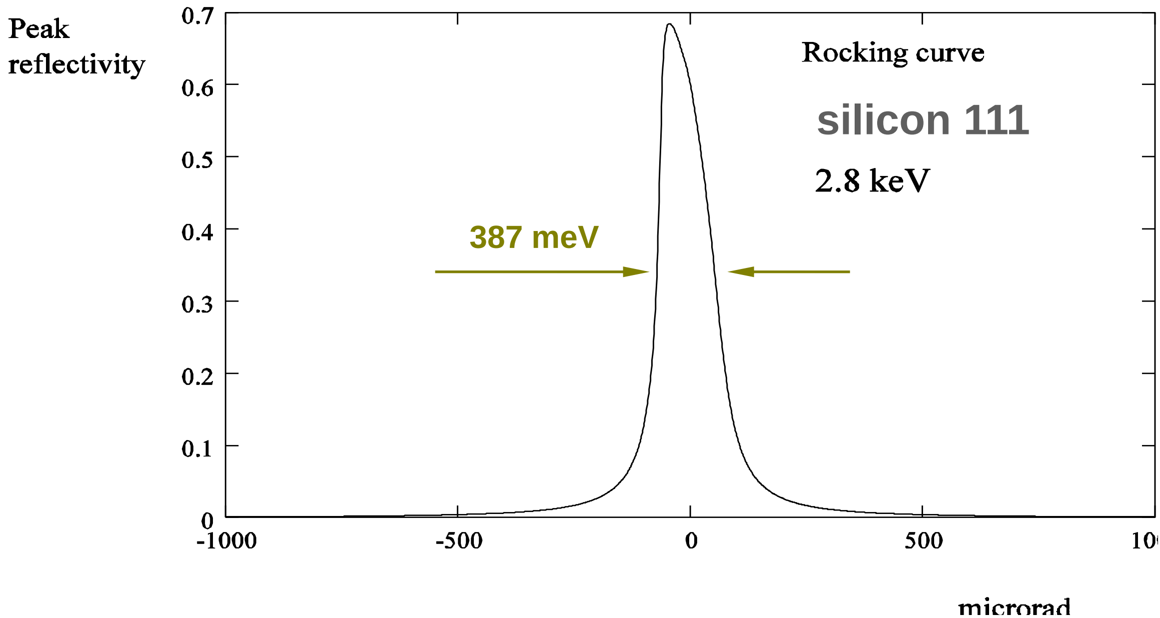
$$\nu = 1 - \delta - i\eta$$

$$n\lambda = 2d\left[1 - \frac{4d^2}{n^2}\left(\frac{\delta}{\lambda^2}\right)\right] \cdot \sin\Theta_B$$



A. E. Sandström,
Handbuch Physik XXX, 1952 p.78

calculated CRYSTAL RESPONSE



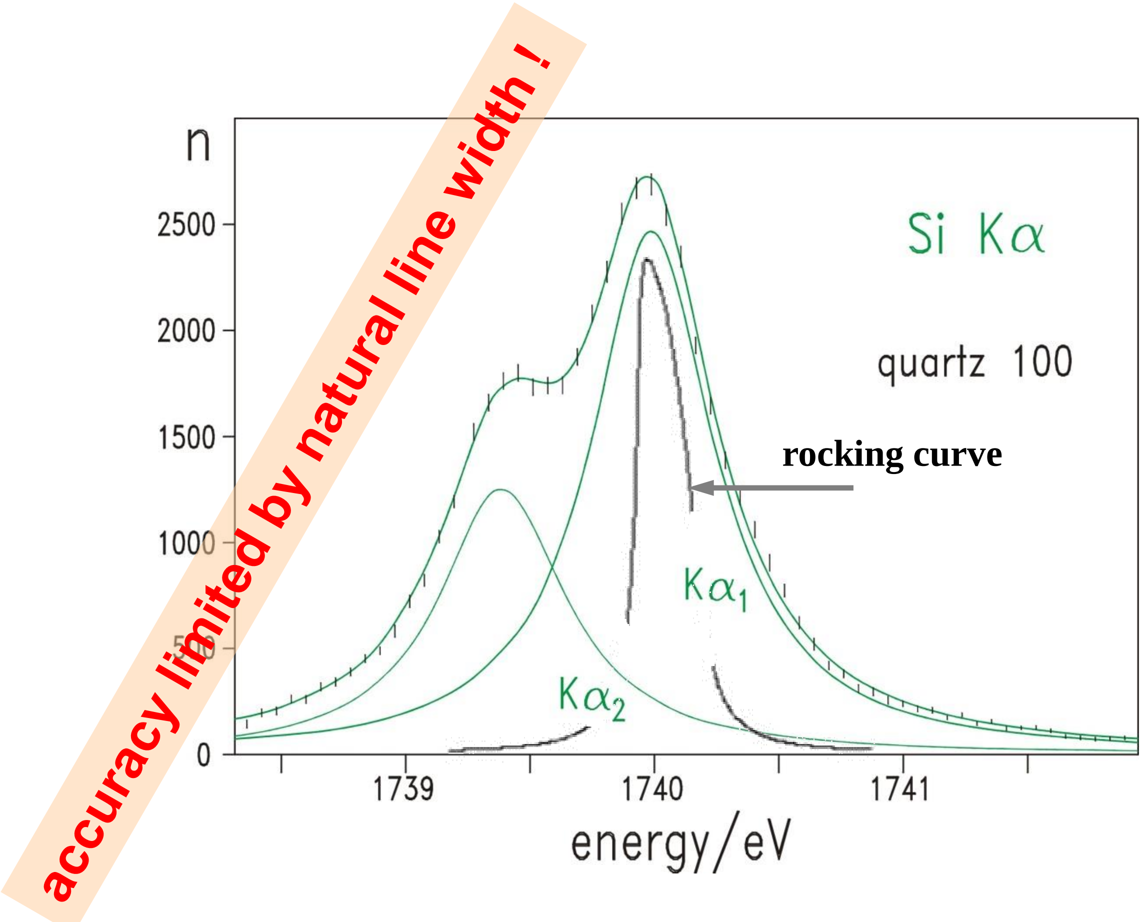
diffraction theory

XOP2 code
plane crystal

response for real crystal mounting?

no ***narrow*** *few keV γ lines*

CALIBRATION *by fluorescence X-rays*



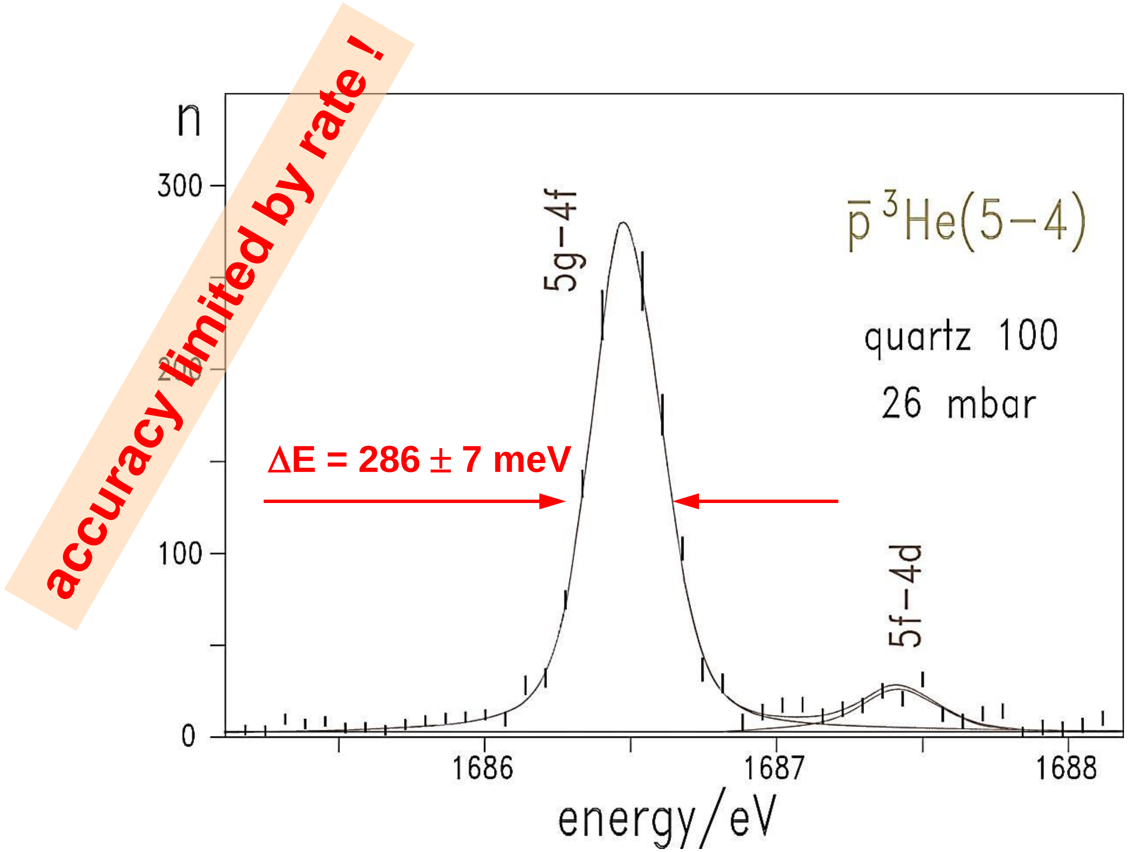
closest to energy of $\bar{p}H(3d\text{-}2p)$

excitation of Si X-rays by means of X-ray tube

high rate

large line width and satellites - resolution hardly measurable

RESPONSE FUNCTION *from exotic atoms*



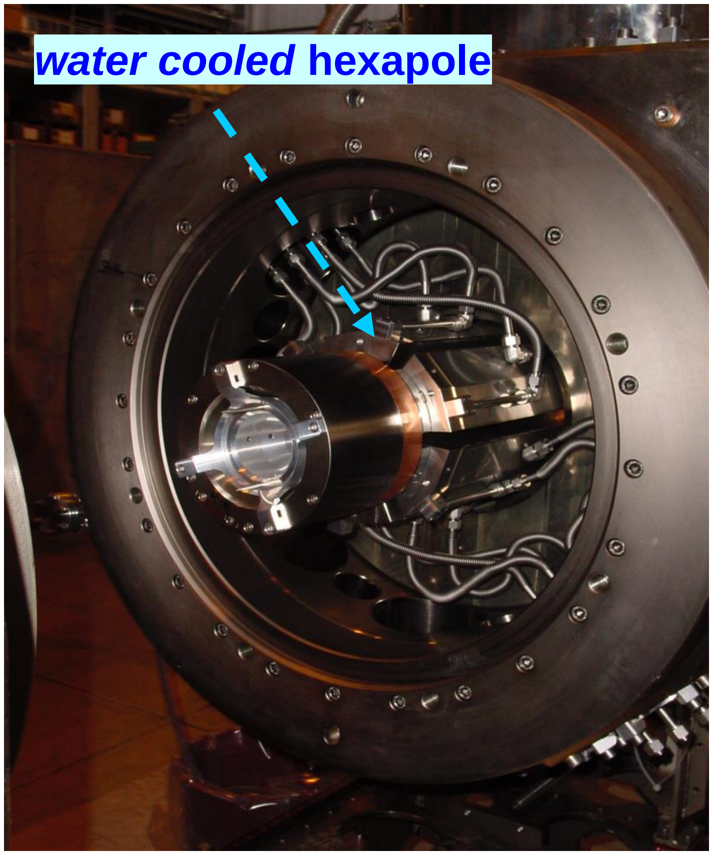
closest to energy of $\bar{p}H(3d\text{-}2p)$

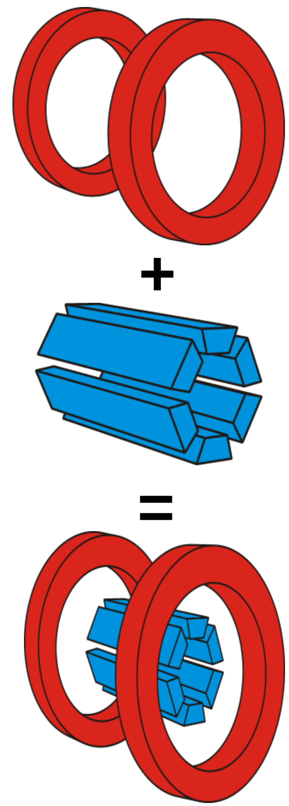
920 events

3 days

SPECTROMETER RESPONSE new approach: ECRIT

ECRIT = Electron Cyclotron Resonance Ion Trap





Superconducting coils

- *cyclotron trap*

permanent hexapole

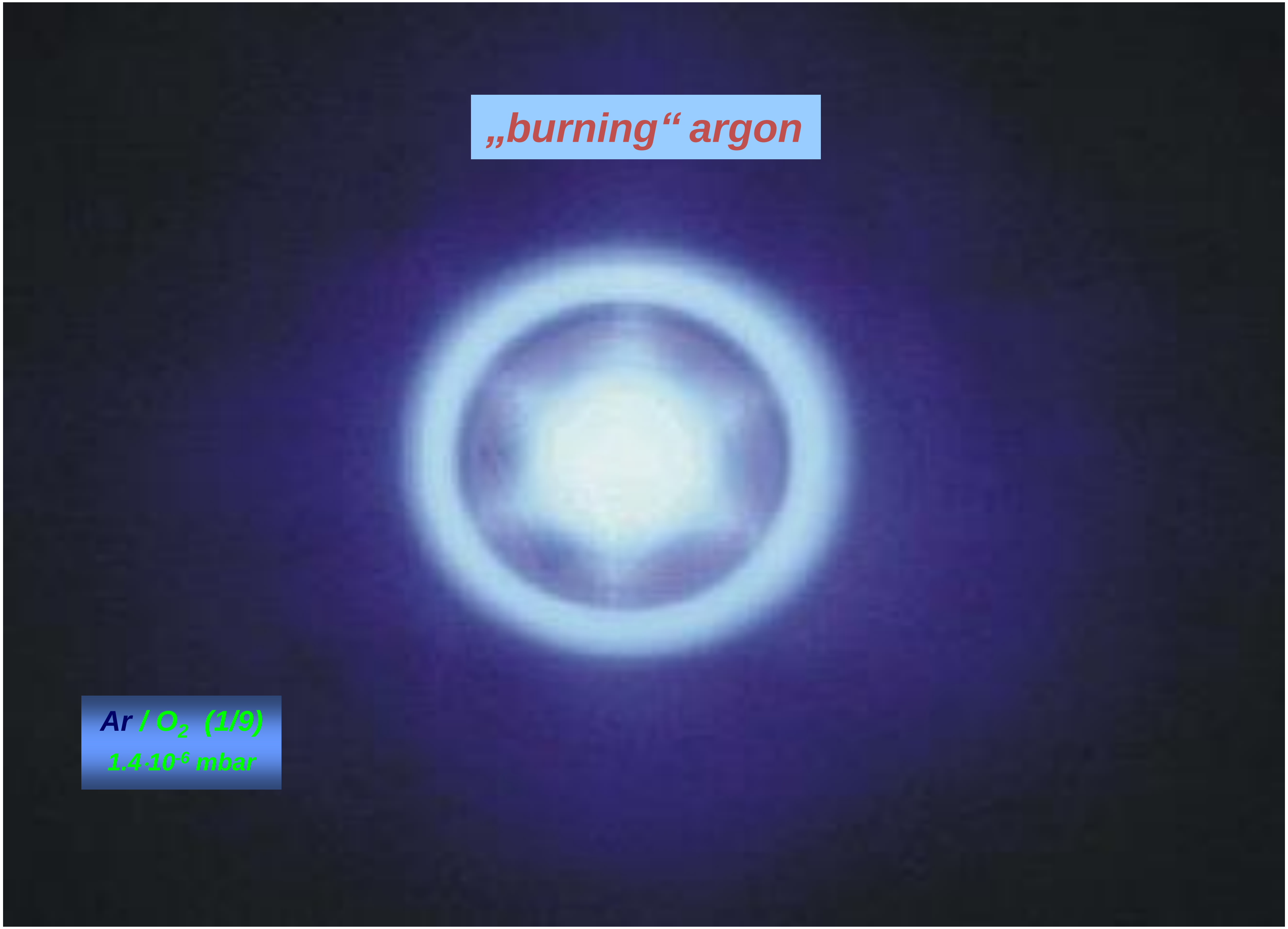
- *AECR-U type*
- *1 Tesla at the hexapole wall*
- *open structure*

large mirror ratio = 4.3

B_{max} / B_{min} !

S. Biri, L. Simons, D. Hitz et al., Rev. Sci. Instr., 71 (2000) 1116

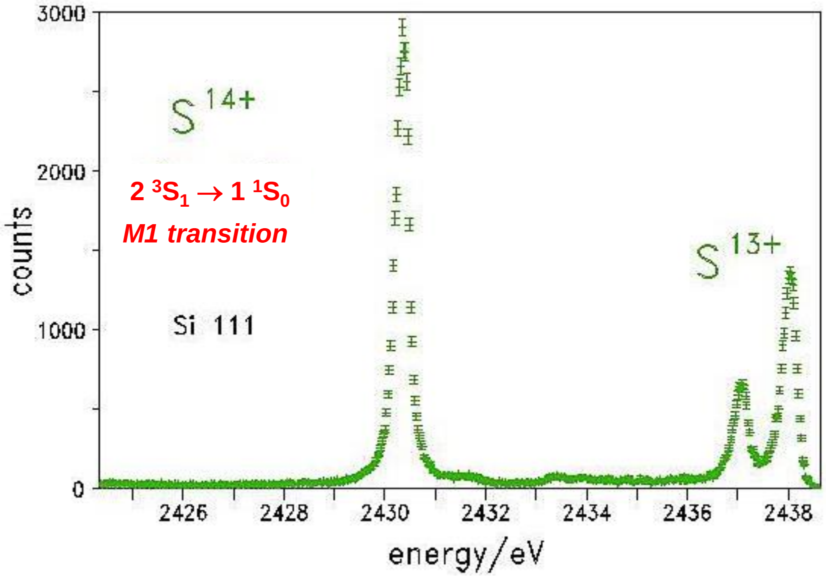
K. Stiebing, Frankfurt – design assistance

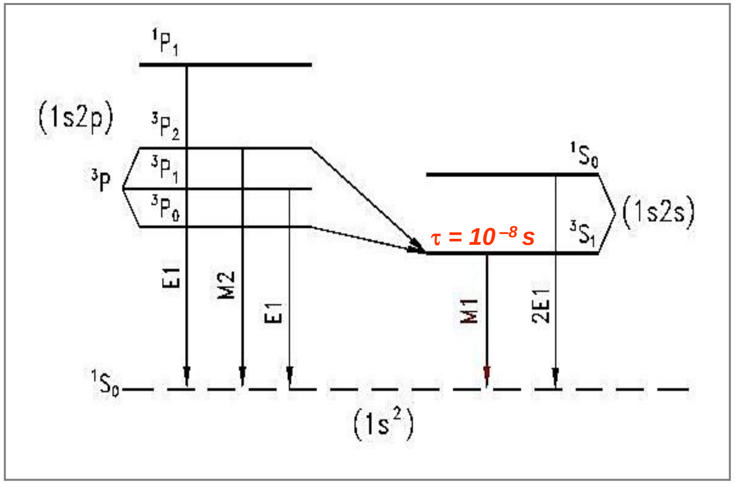

„burning“ argon
Ar / O2 (1/9)
1.4·10-6 mbar

SPECTROMETER RESPONSE at πH Lyman ENERGIES

M1 transitions **in He - like**

S	$\leftrightarrow$	**πH(2p-1s)**
Cl	$\leftrightarrow$	**πH(3p-1s)**
Ar	$\leftrightarrow$	**πH(4p-1s)**





30000 events in line (3 h) $\leftrightarrow$ tails can be fixed with sufficient accuracy

to be compared with Monte-Carlo ray tracing folded with plane crystal response

D.F.Anagnostopoulos et al., Nucl. Instr. Meth. B 205 (2003) 9
D.F.Anagnostopoulos et al., Nucl. Instr. Meth. A 545 (2005) 217

EXPERIMENT III

How to achieve ultimate energy determination and resolution

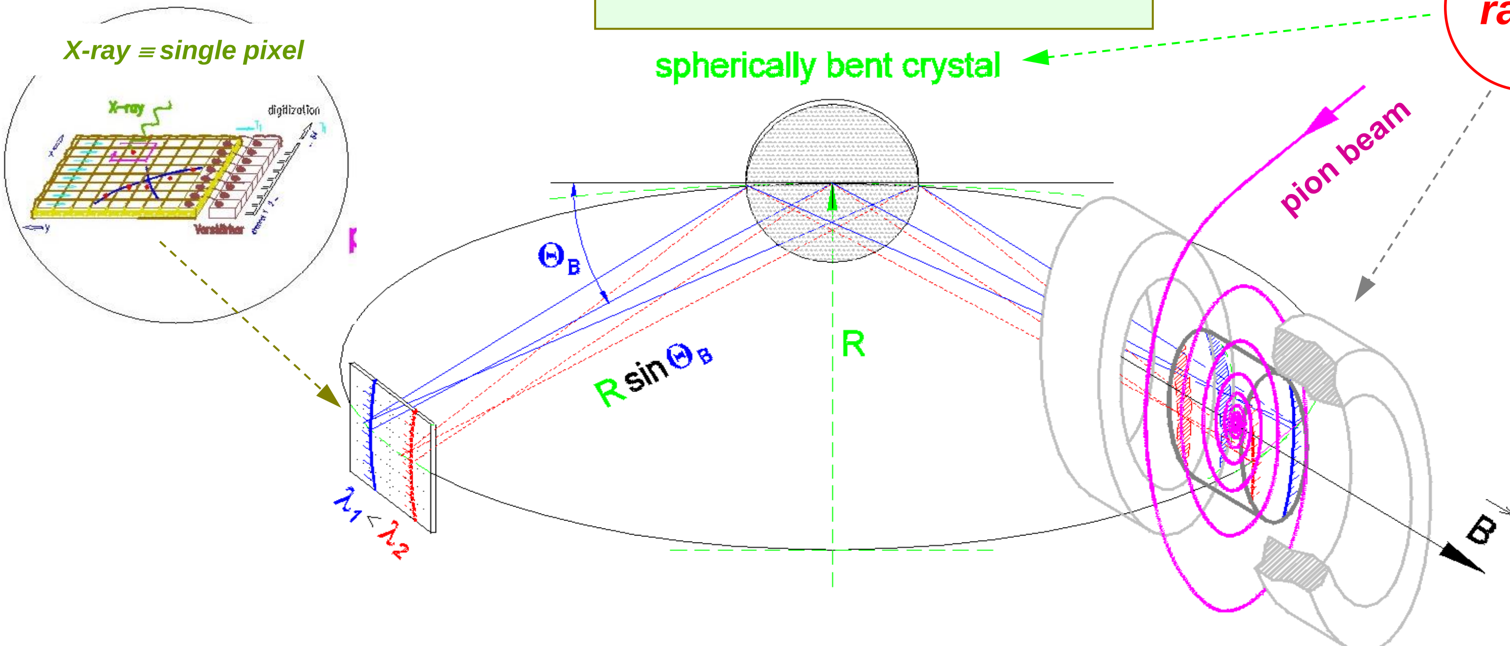
<u>together</u> with

sufficient count rate?

JOHANN-TYPE SET-UP

ultimate energy resolution

rate!



position-sensitive detector
Charge-Coupled Device (CCD)

cyclotron trap
gas cell

<u>position & energy resolution</u>

⇒ **background reduction I**
by analysis of hit pattern

high <u>stop density</u>

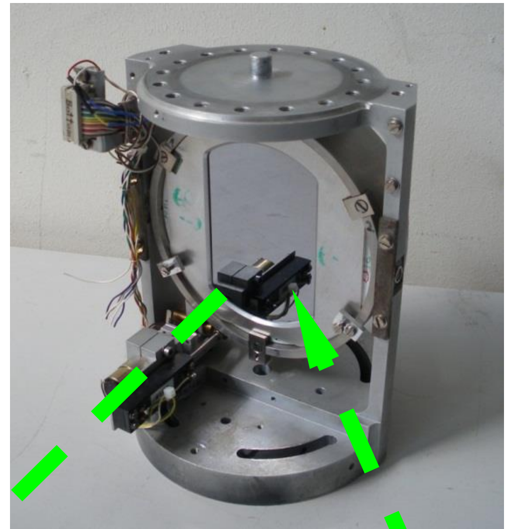
⇒ high X - ray line yields
⇒ bright X - ray source

BRAGG CRYSTAL

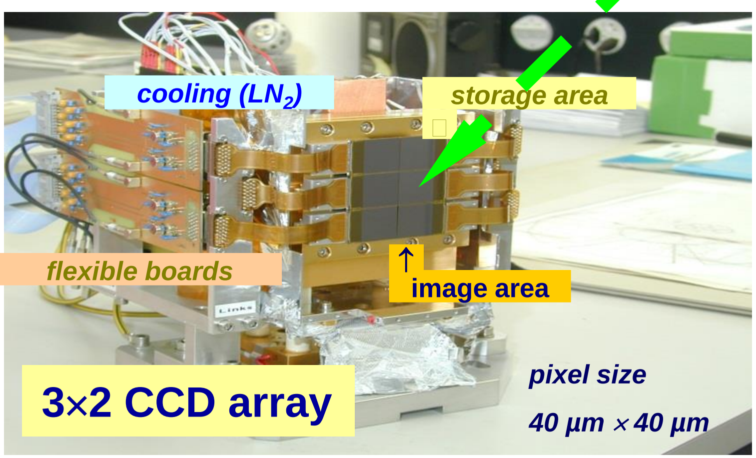
Si 111

spherically curved

R = 3 m
Φ = 10 cm



Large - Area Focal Plane Detector

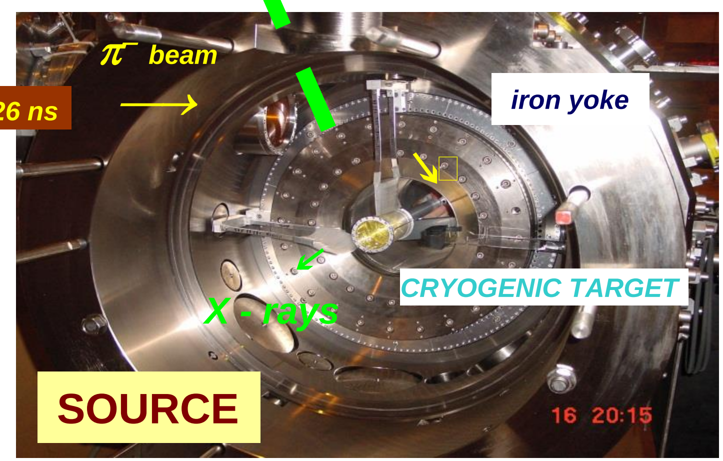


CYCLOTRON TRAP

one coil removed

10^9 π/s

$\tau_{\pi\pm}$ = 26 ns



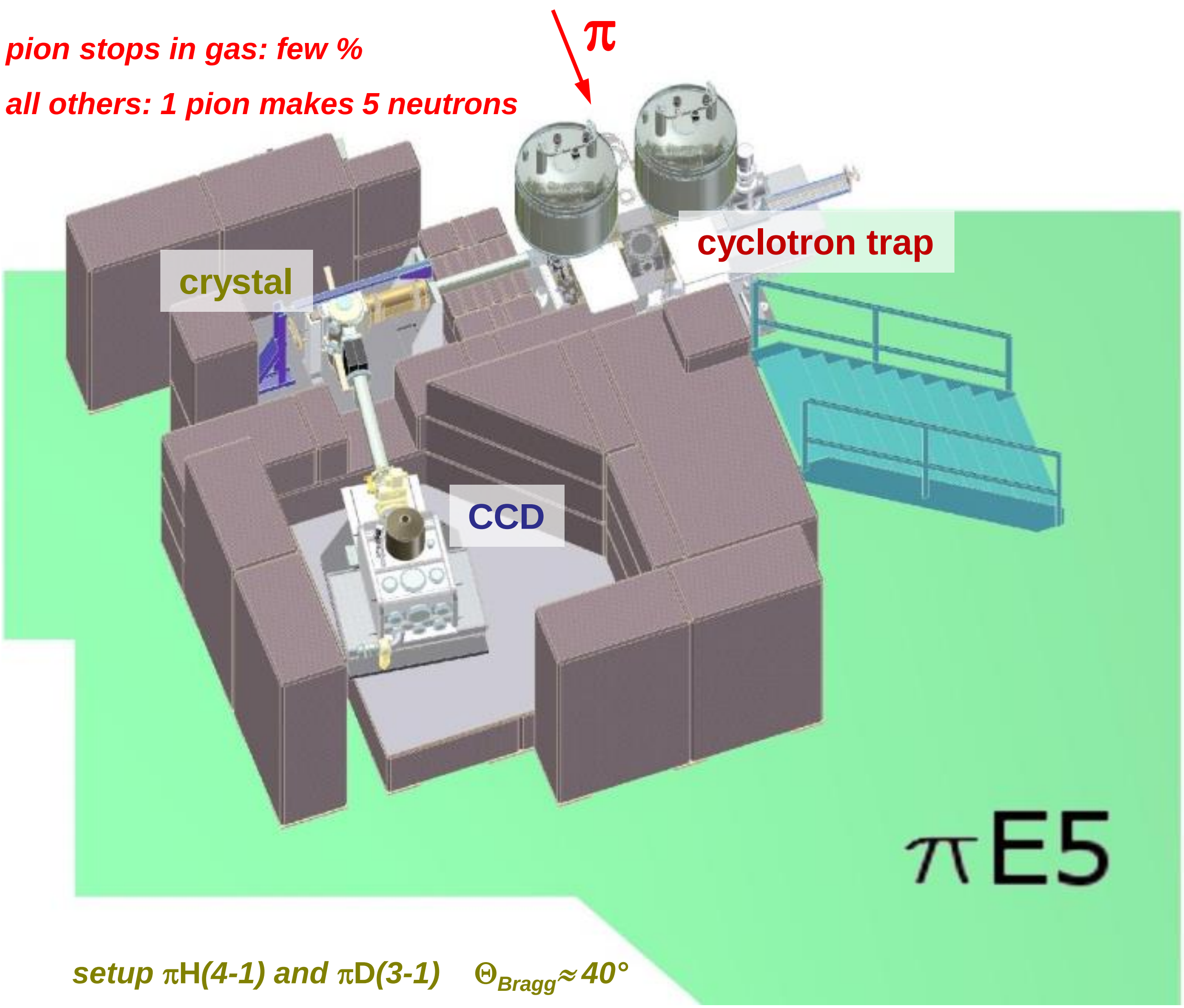
N. Nelms et al., Nucl. Instr. Meth 484 (2002) 419

see talk by M. Jabua

TYPICAL SET-UP at PSI

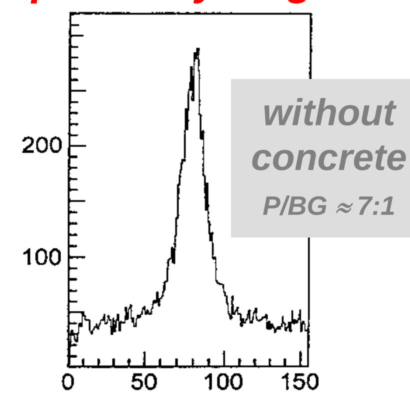
pion stops in gas: few %

all others: 1 pion makes 5 neutrons

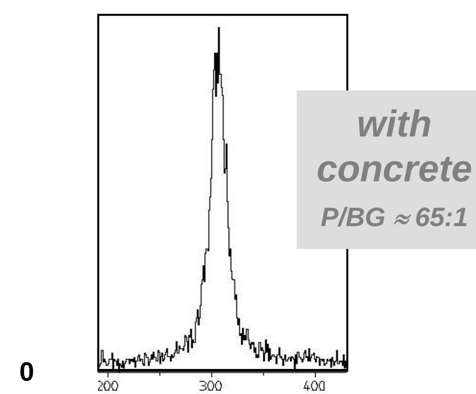


setup πH(4-1) and πD(3-1) $\Theta_{Bragg} \approx 40°$

pionic hydrogen



peak/background x 10



background reduction II

- MOTIVATION
- EXOTIC ATOM
- EXPERIMENTAL APPROACH
- **SOME RESULTS**

PION – NUCLEON

SCATTERING LENGTHS

„QCD Lamb shift“

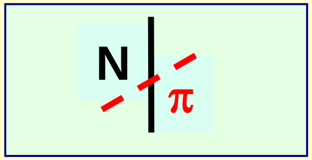
HYDROGEN & DEUTERIUM - ORIGIN OF ε_{1s}

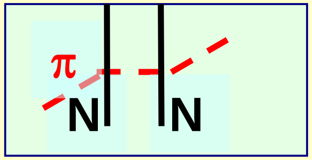
πH *elastic scattering* $\pi^- p \rightarrow \pi^- p$

$+ \ \ldots$

πD *coherent sum* $\pi^- p \rightarrow \pi^- p + \pi^- n$

$+ \ \ldots$



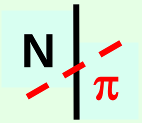


HYDROGEN - ORIGIN OF Γ_{1s}

πH *scattering* $\pi^- p \rightarrow \pi^0 n + n\gamma$

CEX = charge exchange

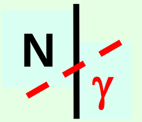
CEX scattering



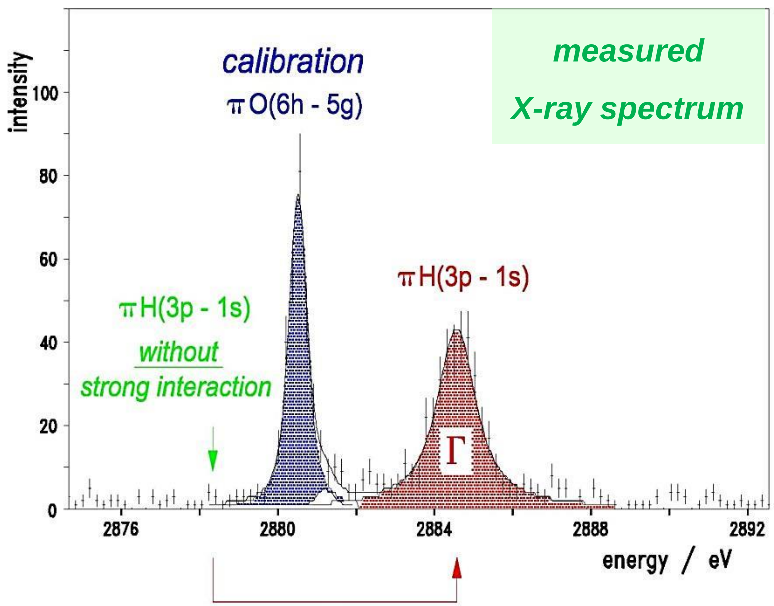
BR P well known from experiment

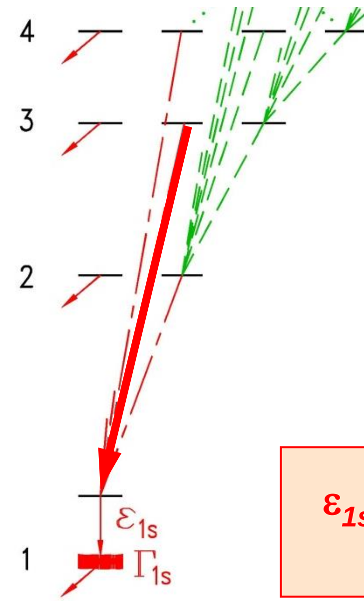
$P = \pi^0 n / n\gamma = 1.546 \pm 0.009$

radiative capture



PIONIC HYDROGEN 3p-1s transition





$$E_B^{\pi H} = -3238\,\mathrm{eV}$$

$$a_{Bohr}^{\pi H} = \quad 140\,\mathrm{fm}$$

ε_{1s} = + 7.086 ± 0.009 eV

(± 0.13%) *final*

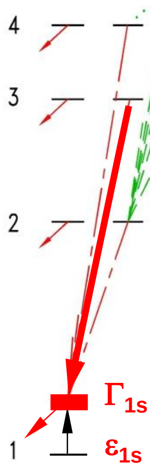
	scattering lengths	*experiment*	*Trueman correction*	χPT *
πH	$\varepsilon_{1s} \propto a_{\pi^- p \to \pi^- p} \propto a^+ + a^- + \ldots$	± 0.2%	… ≈ 1%	+ (–9.0 ± 3.5)%
	$\Gamma_{1s} \propto (a_{\pi^- p \to \pi^0 n})^2 \propto (a^-)^2 + \ldots$	± 2.5%	… ≈ 1%	+ (+0.5 ± 1.0)%
πD	$\varepsilon_{1s} \propto a_{\pi^- d \to \pi^- d} \propto 2 \cdot a^+ + \ldots$	± 1.3%	… ≈ 1%	+ ± 4%

** J. Gasser et al., Phys. Rep. 456 (2008) 167*
M. Hoferichter et al., Phys. Lett. B 678 (2009) 65
V. Baru et al., Phys. Lett. B 694 (2011) 473

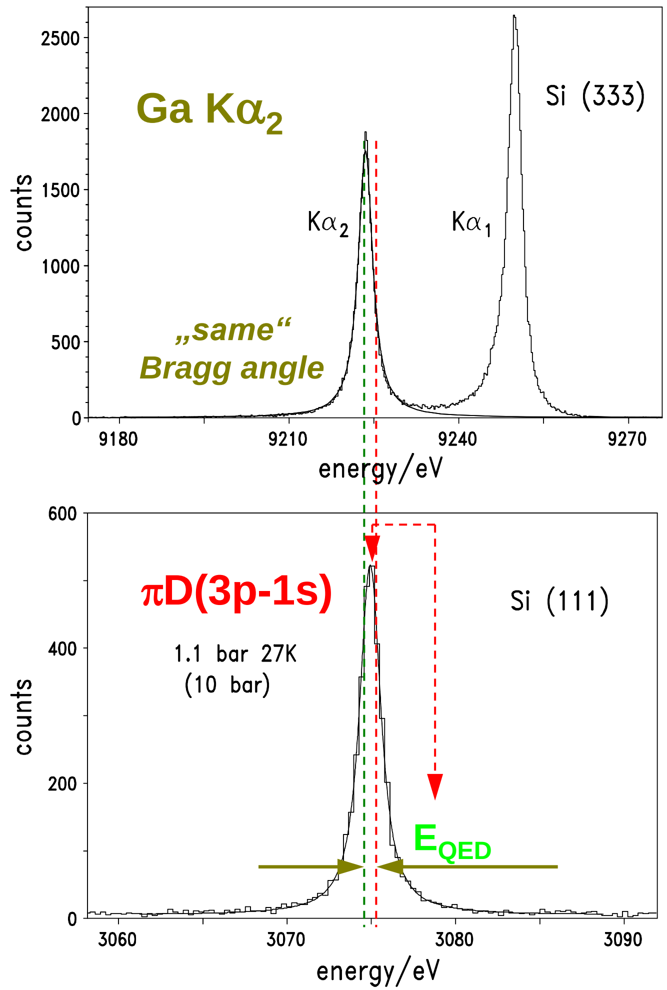
PIONIC DEUTERIUM

energy calibration

strong interaction



repulsive



PhD thesis: Th. Strauch, Cologne 2009
Th. Strauch et al., Phys.Rev.Lett.104 (2010)142503; Eur. Phys.J A 47 (2011)88

target material: GaAs

by chance: tabulated energy
<u>also</u> from GaAs
$\Rightarrow$ no chemical shift

3 bar
10 bar
22 bar } ***no molecule formation seen***

$\varepsilon_{1s} = -2.356 \pm 0.031$ (± 1.3%)

uncertainties
± 27 meV Ga Kα_2
± 10 meV statistics
± 8 meV pion mass
± 5 meV systematics
± 2 meV QED

πN *isospin scattering lengths* a^+ *and* a^-

Δ exp ≈ 2 × Δ theory - no LEC f_1 in NLO

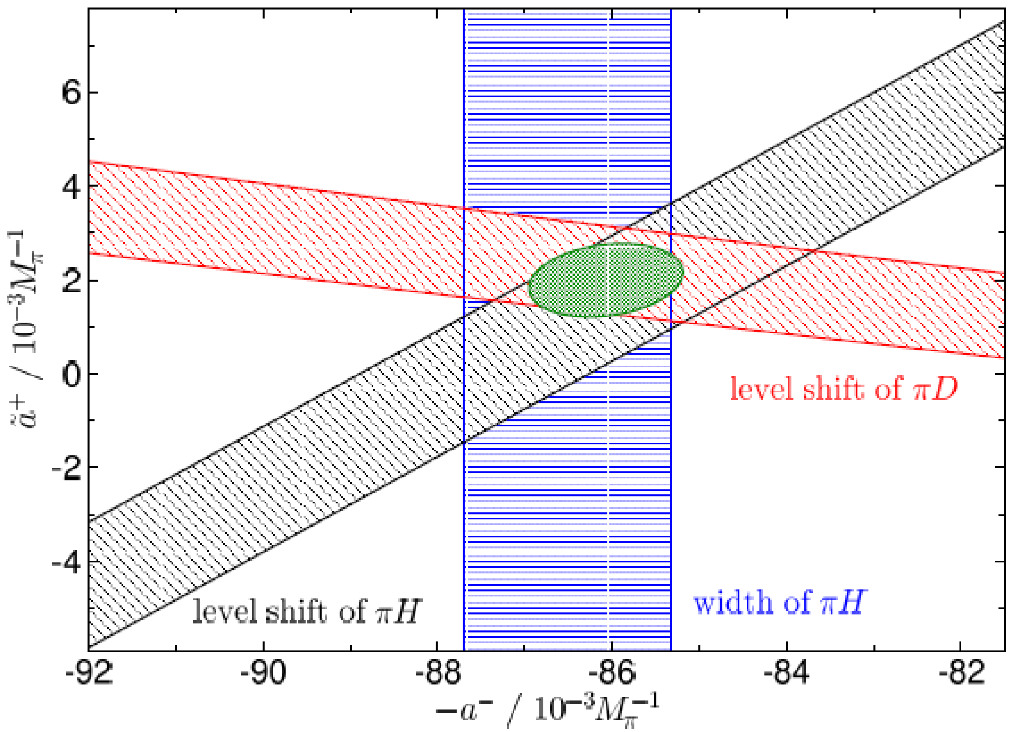


FIG. 2: Combined constraints in the $\tilde{a}^+$–a^- plane from data on the width and energy shift of πH, as well as the πD energy shift.

Δ exp << Δ theory - LEC f_1

Δ exp << Δ theory - LEC f_1

- **constistency ✓**
- **$a^+ > 0$!**

χPT: V. Baru, C. Hanhart, M. Hoferichter, B. Kubis, A. Nogga, and D. R. Phillips, Phys. Lett. B 694 (2011) 473

data: πH - R-98.01 : D. Gotta et al., Lect. Notes Phys. 745 (208) 165 (preliminary)

πD - R-06.03 : Th. Strauch et al., Eur. Phys. J. A 47 (2011) 88 (final)

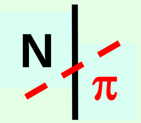
PION

PRODUCTION / ABSORPTION

$$NN \Leftrightarrow \pi NN$$

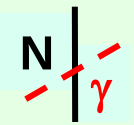
HYDROGEN & DEUTERIUM - ORIGIN OF Γ_{1s}

CEX scattering



πH *scattering* $\pi^- p \rightarrow \pi^0 n + n\gamma$

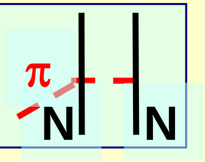
radiative capture



BR are well known from experiment

πD *absorption* $\pi^- d \rightarrow nn + nn\gamma$

„true" absorption



NN $\Leftrightarrow$ πNN threshold parameter α

charge symmetry *detailed balance (T invariance)*

$$\sigma_{\pi^- d \to nn} \quad \leftrightarrow \quad \sigma_{\pi^+ d \to pp} \quad \leftrightarrow \quad \sigma_{pp \to \pi^+ d}$$

$NN \quad {}^3S_1(I=0) \to {}^3P_1(I=1)$

NN $\Leftrightarrow$ πNN threshold parameter α

charge symmetry | detailed balance

$$\sigma_{\pi^- d \to nn} \leftrightarrow \sigma_{\pi^+ d \to pp} \leftrightarrow \sigma_{pp \to \pi^+ d}$$

$NN \quad {}^3S_1(I=0) \to {}^3P_1(I=1)$

πD

$$\Im\, \mathbf{a}_{\pi \mathrm{D}} \propto \Gamma_{\pi^- \mathrm{d} \to \mathrm{nn}} + \Gamma_{\pi^- \mathrm{d} \to \mathrm{nn}\gamma} \propto \alpha$$

directly from Γ_{1s}

π production

$$\sigma_{pp \to \pi^+ d} \to \alpha\, C_0^2\, \eta + \cancel{\beta\, C_1^2\, \eta^3}$$

extrapolation to threshold

$$\boxed{\eta = k_\pi / m_\pi}$$

NN $\Leftrightarrow$ πNN threshold parameter α

charge symmetry *detailed balance*

$$\sigma_{\pi^- d \to nn} \leftrightarrow \sigma_{\pi^+ d \to pp} \leftrightarrow \sigma_{pp \to \pi^+ d}$$

$NN \quad {}^3S_1(I=0) \to {}^3P_1(I=1)$

πD

$$\Im\, a_{\pi D} \propto \Gamma_{\pi^- d \to nn} + \Gamma_{\pi^- d \to nn\gamma} \propto \alpha$$

directly from Γ_{1s}

π production

$$\sigma_{pp \to \pi^+ d} \to \alpha\, C_0^2\, \eta + \cancel{\beta\, C_1^2\, \eta^3}$$

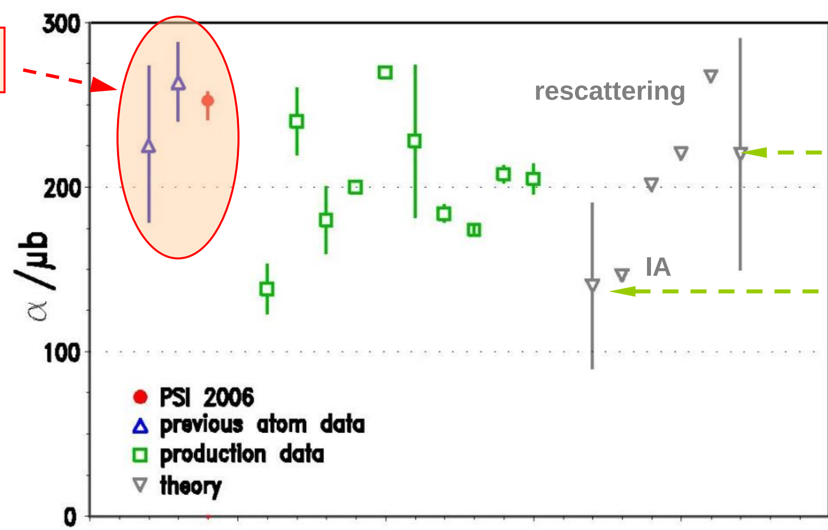
extrapolation to threshold $\eta = k_\pi / m_\pi$

exotic-atom results

Th. Strauch, PhD thesis, Cologne 2009

Th. Strauch et al., Phys.Rev.Lett.104 (2010)142503

Th. Strauch et al., Eur.J.Phys.47 (2011)88



χPT NLO

χPT LO

χPT

at present

$\Delta\alpha/\alpha \approx 30\%$

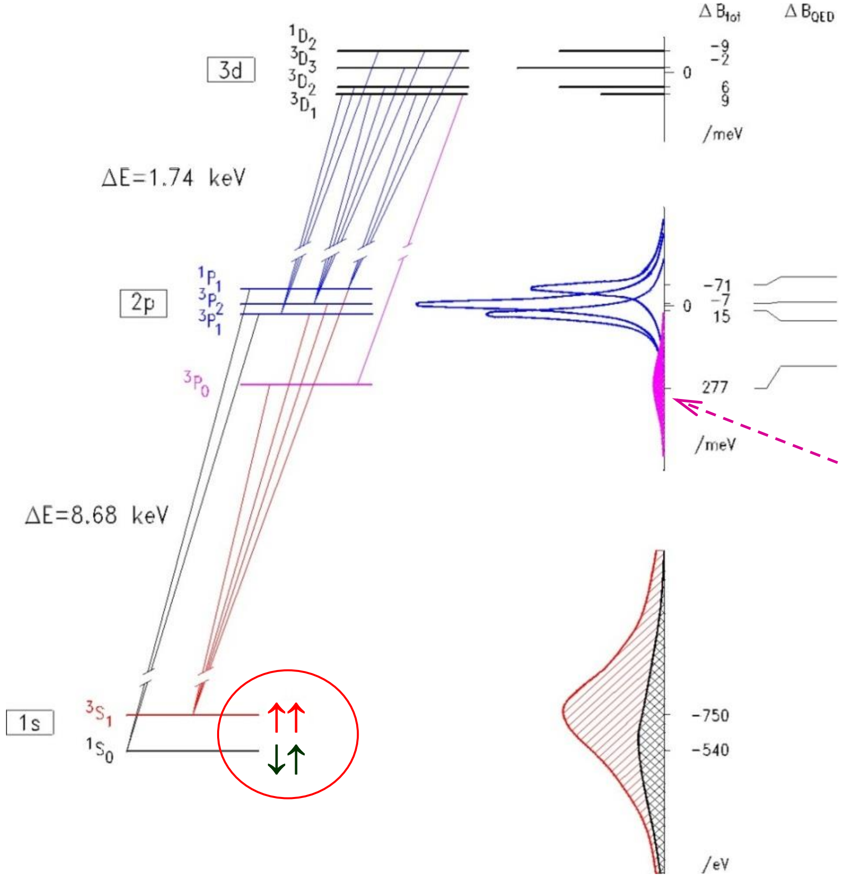
$\to$ few % !?

V. Lensky et al., Eur. Phys. J. A 27 (2006) 37

NUCLEON - ANTINUCLEON

STRONG SPIN - SPIN and SPIN - ORBIT INTERACTION

PROTONIUM - calculated HFS level scheme



s- and p-state strong interaction effects

d state *strong interaction negligible*

p state ***spin-orbit interaction***

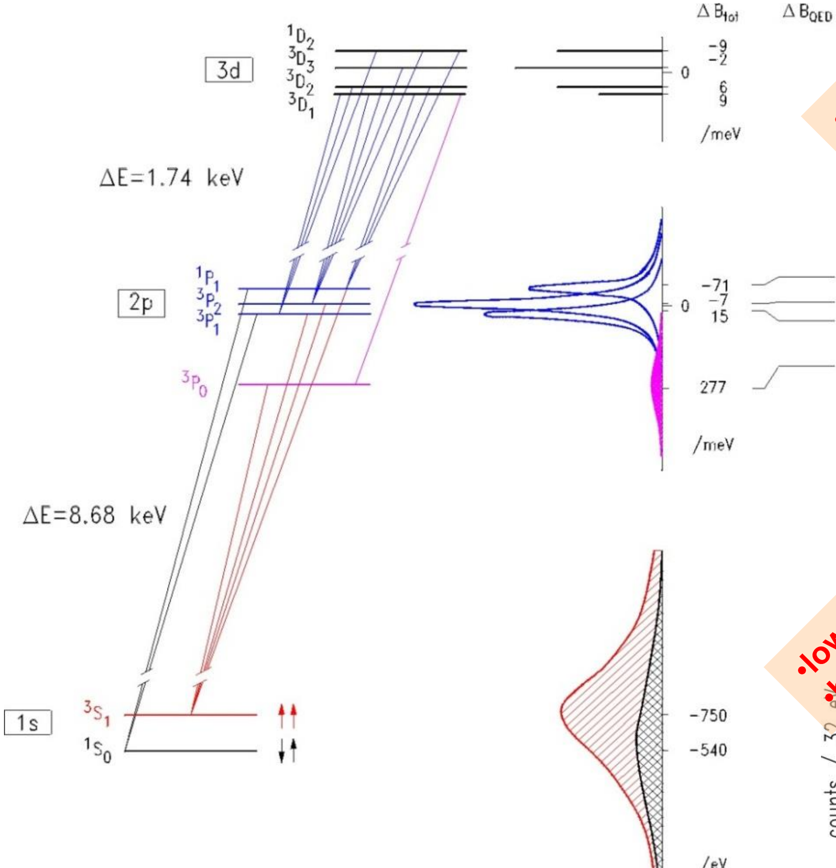
meson exchange:
strongly attractive
isoscalar tensor interaction

Richard, Sainio, Phys. Lett. B (1982)349

s state ***spin-spin interaction***

$\varepsilon > 0$ (<0) ≡ attractive (repulsive) interaction

PROTONIUM - EXPERIMENT

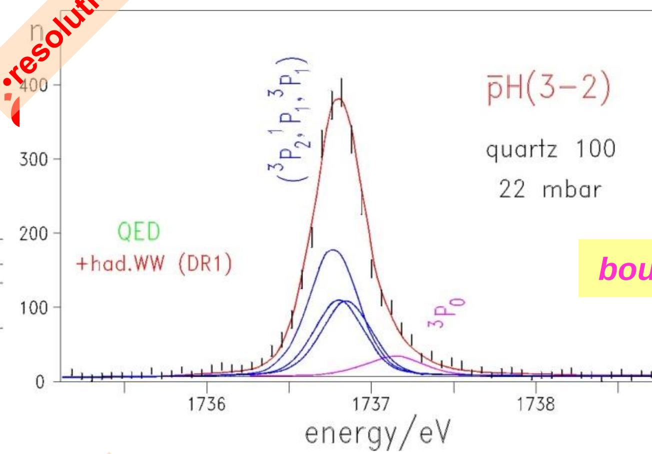


LEAR experiment PS207

M. Augsburger et al., Nucl. Phys. A 658 (1999) 149
D. Gotta et al., Nucl. Phys. A 660 (1999) 283

cyclotron trap + MOS CCD

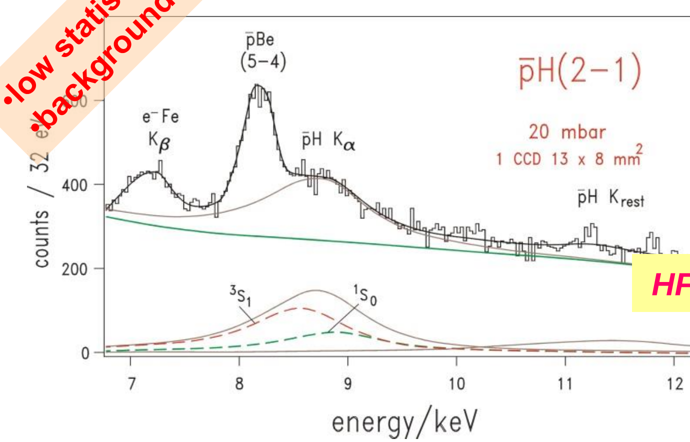
•resolution



bound states ?

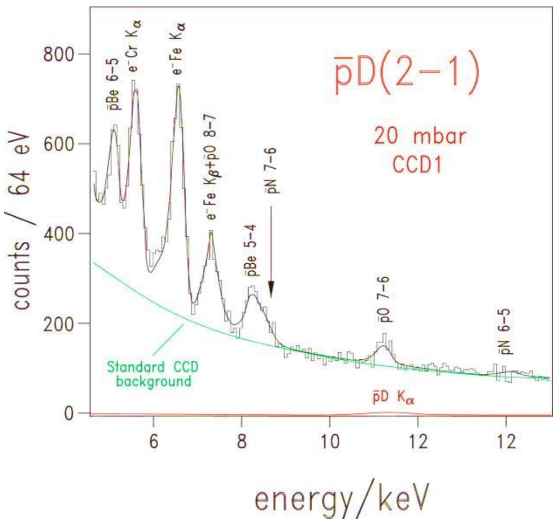
most recent theo. paper:
J. Carbonell,
Nucl. Phys. A 692 (2001) 11

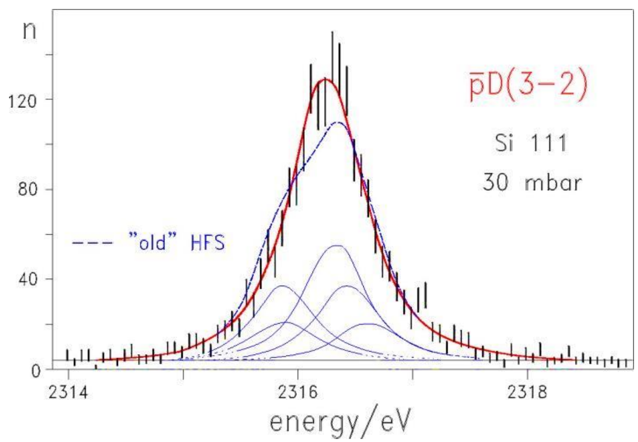
•low statistics
•background



HFS splitting?

ANTIPROTONIC DEUTERIUM





s- and p-state strong interaction effects

ground state **weak signal**

spin average ε_{1s} = - 1050 ± 250 eV

Γ_{1s} = 1100 ± 750 eV

M. Augsburger et al., Phys. Lett. B 461 (1999) 417

2p state ***HFS not resolvable***

spin average ε_{2p} = - 243 ± 26 meV

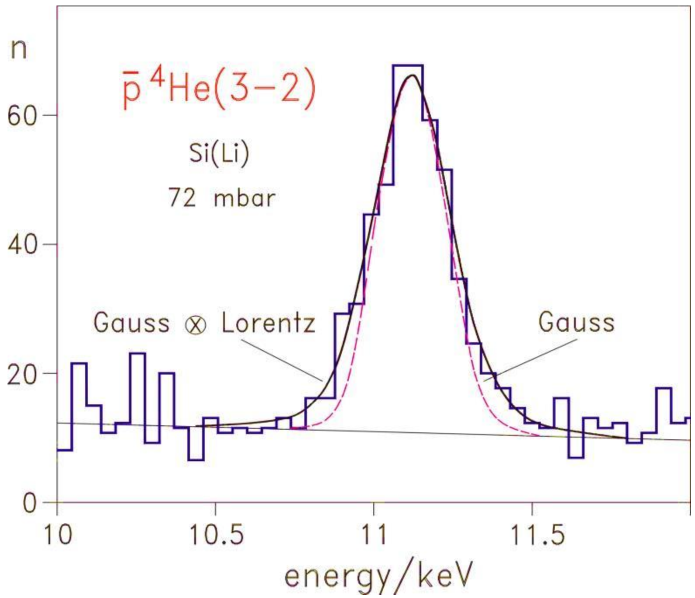
Γ_{2p} = 489 ± 308 meV

D. Gotta et al., Nucl. Phys. A 660 (1999) 283

NUCLEON - ANTINUCLEON

ANNIHILATION STRENGTH

ANTIPROTONIC HELIUM



M. Schneider et al., Z. Phys. A 338 (1991) 217

LEAR experiment PS175

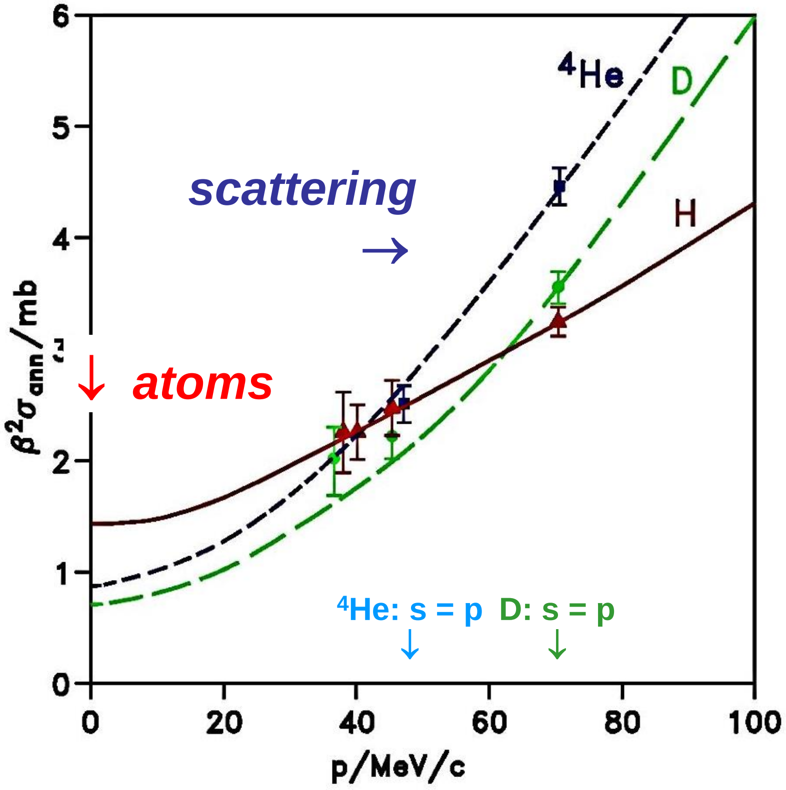
isotope effects

spin average		ε / eV	Γ / eV
$\bar{p}\,^3He$	2p	– 17 ± 5	25 ± 9
$\bar{p}\,^4He$	2p	– 18 ± 2	45 ± 5

single - nucleon annihilation ?

$$\Gamma_{A(Z,N)} \propto Z \cdot \Gamma_{\bar{p}n} + N \cdot \Gamma_{\bar{p}p}$$

ATOM DATA ⇔ LOW-ENERGY SCATTERING



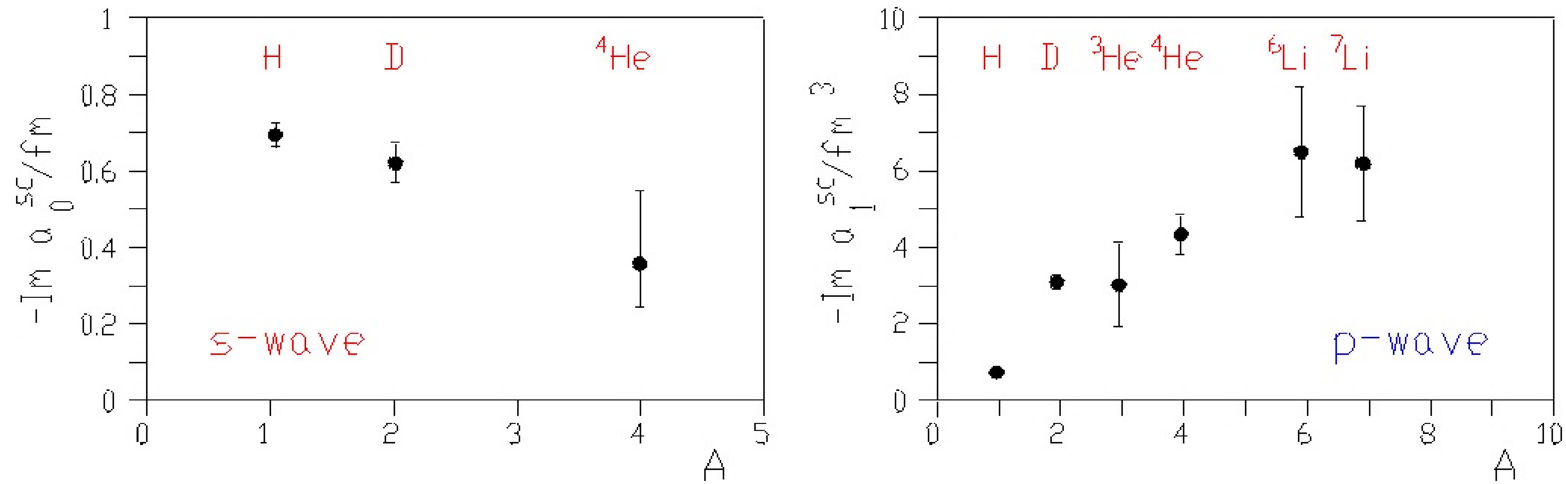
	atom	*scattering*
	Trueman formula	*effective range fit*
Im a_s	**- 0.69±0.3**	**- 0.69±0.04 fm**
Im a_p	**- 0.77±0.6**	**- 0.75±0.07 fm**

<u>striking</u> agreement

data: LEAR – PS201(OBELIX)

discussion and references: K. Protasov et al., Eur. Phys. J. A 7 (2000) 429

ANNIHILATION STRENGTH ⇔ NUCLEAR MASS



K. Protasov et al., Eur. Phys. J. A 7 (2001) 429

supplemantary data: PS176

saturation ?

seen also in optical potential analyses

$$U_{opt} \propto a \cdot \rho\,(r)$$

A. Gal, E. Friedman and C.J. Batty, Phys. Lett. B491 (2000) 219

qualitatively – strong annihilation suppresses wave function inside matter

e. g. $\varepsilon_{1s} < 0$ for $\bar{p}p$

RETROSPECT and OUTLOOK

Prediction **1947** ***Fermi & Teller***

First X-rays from pionic and antiprotonic atoms

Rochester 1952

X-Rays from Mesic Atoms*

M. Camac, A. D. McGuire, J. B. Platt, and H. J. Schulte
University of Rochester, Rochester, New York
(Received August 18, 1952)

NaI(Tl) ***inorganic scintillator***

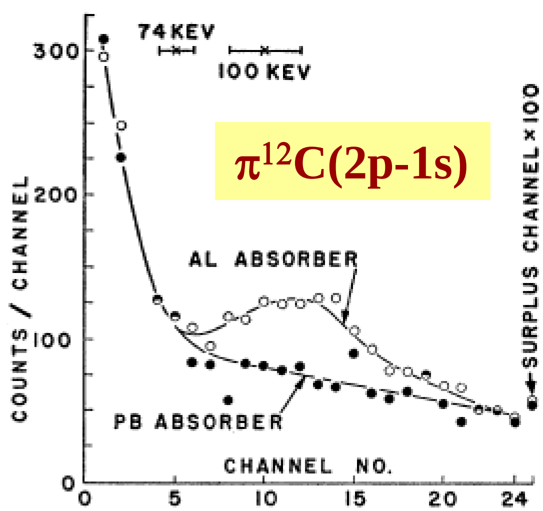


Fig. 1. Pulse-height spectrum from carbon.

CERN 1970

OBSERVATION OF ANTIPROTONIC ATOMS

A. BAMBERGER, U. LYNEN, H. PIEKARZ *, J. PIEKARZ **, B. POVH and H. G. RITTER
Max-Planck-Institut für Kernphysik, Heidelberg, Germany
and CERN, Geneva, Switzerland
and
G. BACKENSTOSS, T. BUNACIU, J. EGGER ***, W. D. HAMILTON ‡ and H. KOCH
Institut für Experimentelle Kernphysik der Universität und des Kernforschungszentrums, Karlsruhe, Germany
and CERN, Geneva, Switzerland

Received 28 August 1970

Ge(Li) ***semiconductor detector***

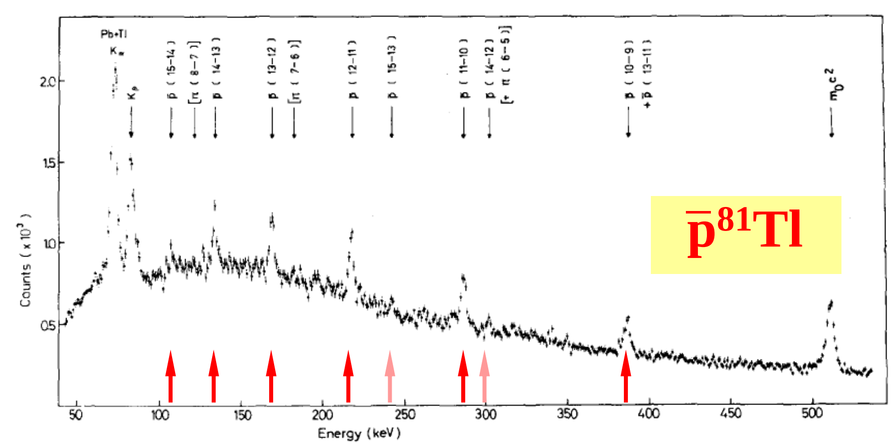


Fig. 2. Antiprotonic X-ray spectrum of $_{81}$Tl obtained from 14×10^6 stopped antiprotons measured with a 10 cm^3 Ge(Li)-detector.

πH(2p-1s) using a crystal spectrometer

first - LAMPFF 1983

PHYSICAL REVIEW C VOLUME 28, NUMBER 6 DECEMBER 1983

Determination of the 2*p*-1*s* transition energy and strong interaction shift in pionic hydrogen using crystal diffraction

A. Forster, E. Bovet,* J. Gimlett, H. E. Henrikson, D. Murray,† R. J. Powers, P. Vogel, and F. Boehm
California Institute of Technology, Pasadena, California 91125

R. Kunselman
University of Wyoming, Laramie, Wyoming 82071

P. L. Lee
California State University of Northridge, Northridge, California 91330

(Received 29 July 1983)

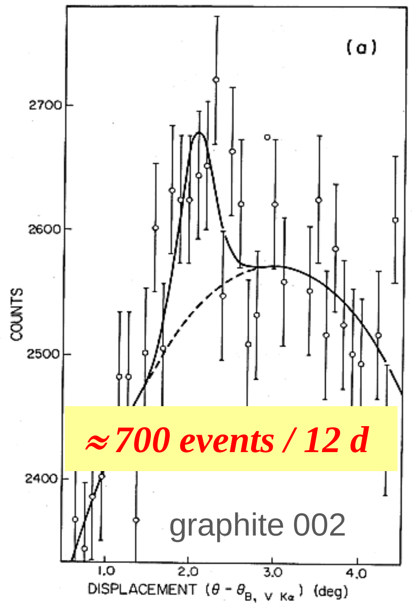
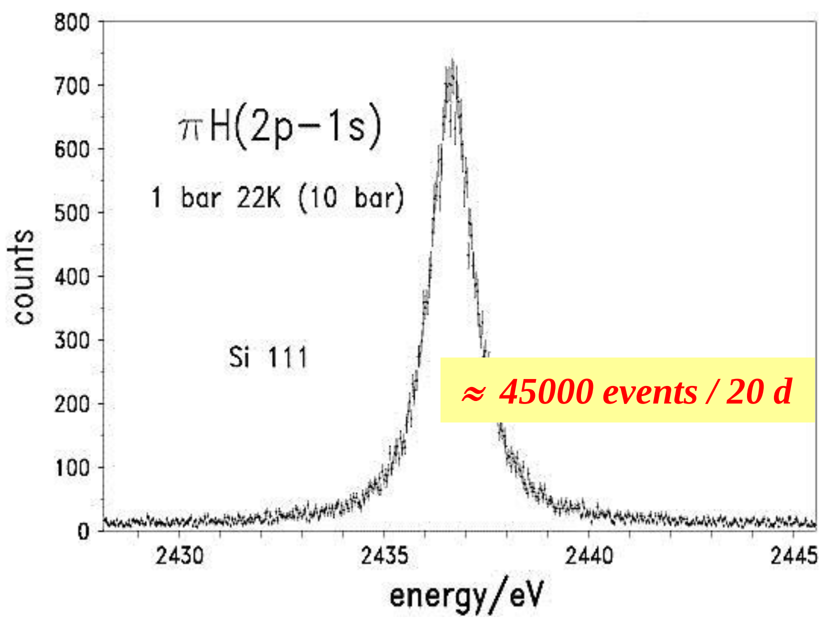


FIG. 7. (a), (b). Pionic hydrogen line

most recent - PSI 2005

πH collaboration exp. R-98.01

http://collaborations.fz-juelich.de/ikp/exotic-atoms



$\bar{p}H(3d-2p)$ using a crystal spectrometer

first - LEAR 1996

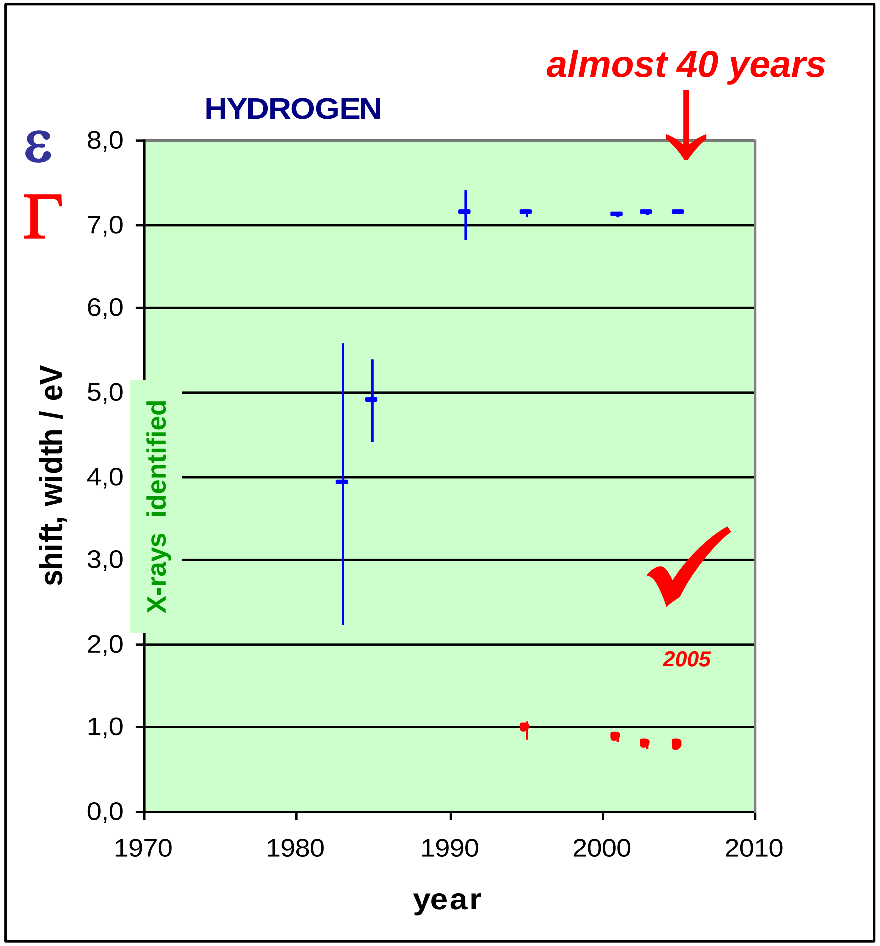
=

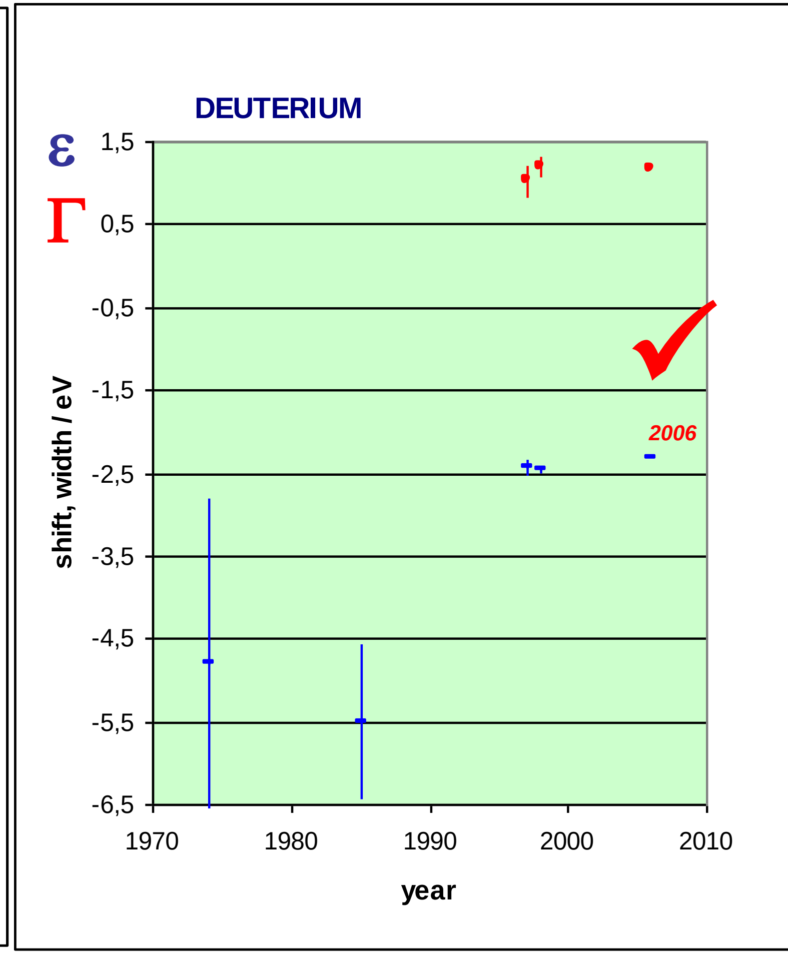
most recent - LEAR 1996

PS 207 collaboration

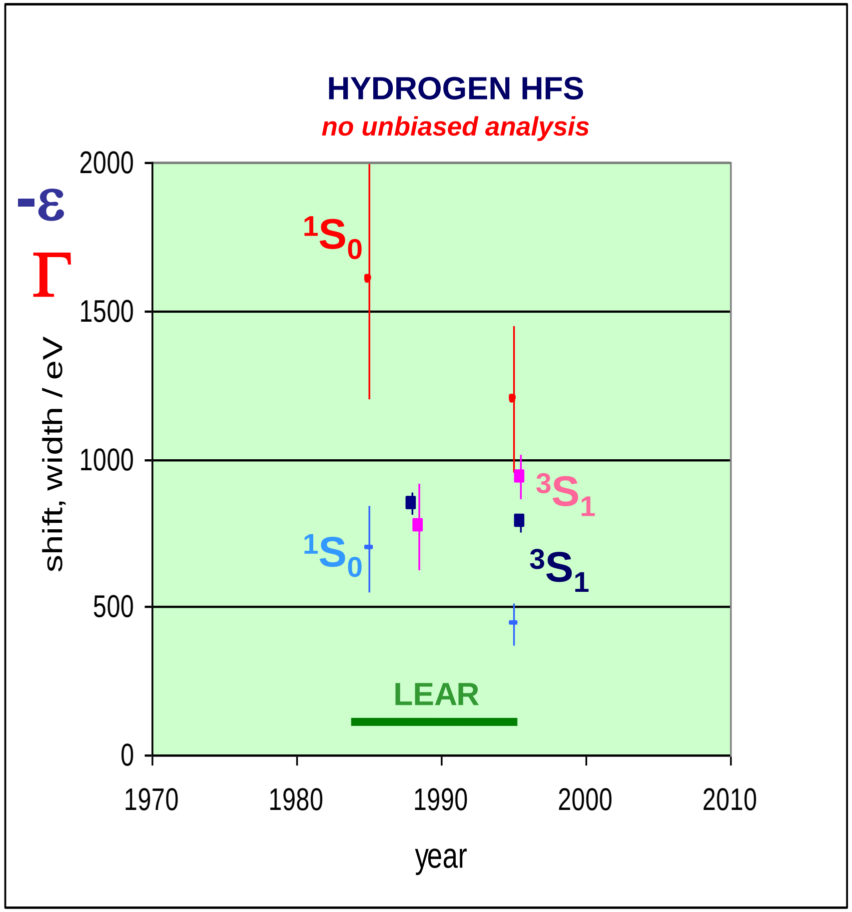
≈ 2000 events / 8 d

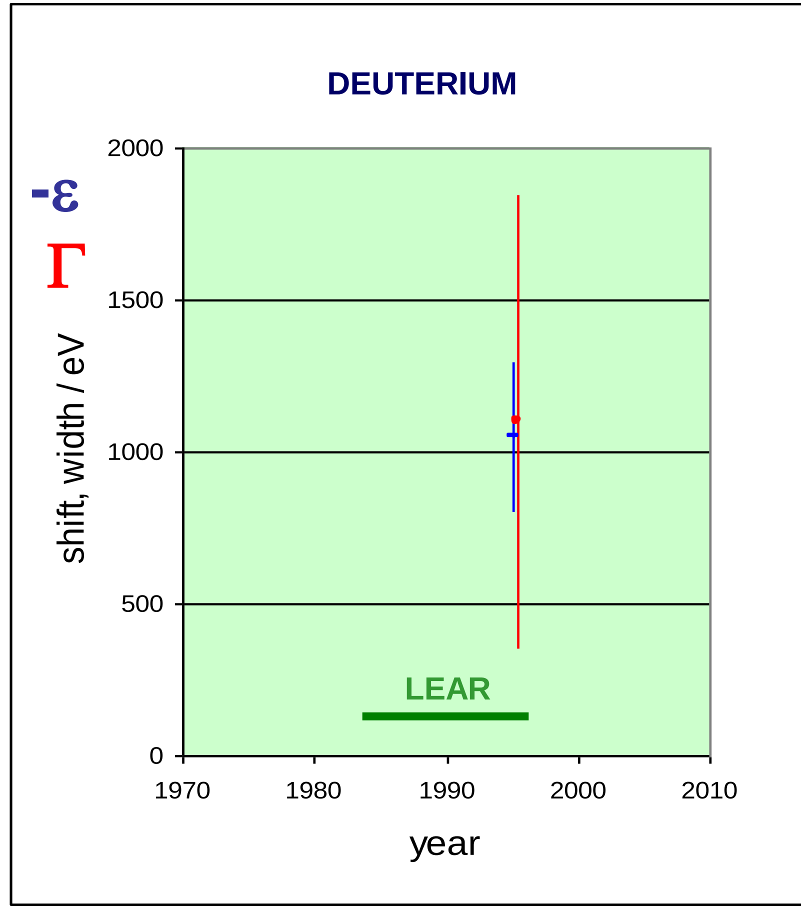
PIONIC HYDROGEN STORY





ANTIPROTONIC HYDROGEN STORY *s-wave*





still a lot to do !

THANK YOU